Economic and climate benefits to the UK of an increased use of bio-based chemicals

Executive Summary

Prepared for the Department for Energy Security and Net Zero

Project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

Headline

By 2050, the UK bio-based chemicals industry has the potential to grow significantly, producing over 2 million tonnes of bio-based chemicals, contributing to 5.2 million tonnes CO2eq GHG savings and £1.6bn in value to the UK economy.

About the study

In December 2022 the Department for Energy Security and Net Zero (formally BEIS) commissioned an independent study to assess the economic and climate benefits to the UK of an increased use of bio-based chemicals. The study aimed to produce quantitative estimates of carbon savings and economic benefits of various biomanufacturing technologies, to highlight areas, in which biomass use in the chemicals sector could best contribute to growing innovation and the economy, while also helping meet the UK's Net Zero ambitions.

UK potential to produce bio-based chemicals

The study used extensive stakeholder engagement though online survey, interview, roundtable meetings and workshops to refine a long list of bio-based chemicals down to a top 13 list of chemicals on which an economic and environmental assessment was performed. Stakeholders consulted during the study included large, medium and small businesses, government officials, academics, banks and trade bodies. In total the study has engaged with 69 individual organisations completed the survey, and 50 organisations were interviewed, covering TRLs 1 to 9.

The chemical selection process centred on three key criteria, 1) production should be credible/achievable (i.e., feedstock and production technologies are available), 2) production should be meaningful (i.e., production/demand would be at a scale sufficient to make a meaningful carbon savings impact, and 3) the potential for production should be plausible/realistic (i.e., there is clear UK interest in the production or use of the chemical).

Several manufacturing concepts were considered for the production of bio-based chemicals, options for production include large scale production of multiple products within biorefineries, single product focussed production within distributed biomanufacturing facilities (biofactories) and the co-processing of biomass and fossil resources within existing petrochemical complexes.

To enable the assessment of economic and environmental impacts resulting from an increase in bio-based chemical and materials production a scenario for production of the 13 target bio-based chemicals from defined feedstock, across 2030, 2040 and 2050 timeframes was created.

Chemicals with developed technology and strong UK stakeholder association were considered to be deployed by 2030, by 2040 all target chemicals are produced in the UK, and by 2050, all bio-based chemical production has been scaled.

The studied chemicals and production scenario is shown in Figure 1.

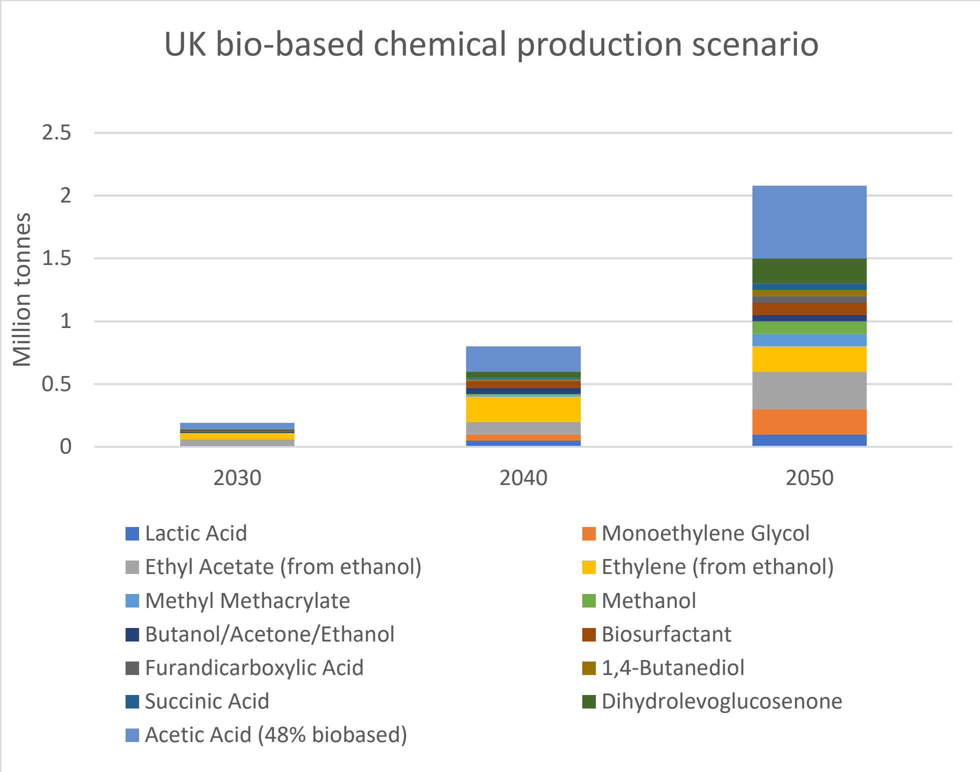

Figure 1. Bio-based chemical production scenario (2030, 2040, 2050)

Although the availability of UK domestic biomass is uncertain, analysis of the scenario shows the UK potential to produce over two million tonnes of the target chemicals. Additionally the chemicals examined are all produced from the sugar fraction of biomass feedstock, therefore with the appropriate development of co-product streams (e.g., protein from grains, and hemicellulose and lignin from lignocellulosic biomass), the actual output of all chemicals could be considerably higher than two million tonnes.

Carbon saving potential

The review demonstrated that the bio-based chemical industry has a significant potential to produce chemicals and materials with a reduced climate change impact; compared to equivalent fossil based chemicals.

Where possible GHG emission savings were drawn from LCA studies based on UK production and therefore using UK process emission data. Where this has not been possible an attempt was made to use UK relevant information.

The GHG saving potential for individual chemicals ranges from 1-9tonnes of CO_2eq per tonne of bio-based chemical, with an average saving of 2.5 tonnes CO_2eq per tonne.

In respect to bioenergy comparisons these results reflect favourably when compared to UK wheat grain derived ethanol for use as road transport fuel. UK bioethanol returns a GHG emission saving of 76-82% against fossil fuel average which equates to 1.9-2.1tonnes CO_2eq per tonne of ethanol.

Based on the production scenarios explored in the study there exists the potential to save 0.48, 2.0 and 5.2 million tonnes of CO_2eq emissions in 2030, 2040 and 2050 respectively.

However it should be recognised that a review of this nature where LCA results are compared across studies and counterfactual fossil based chemical emissions values are derived separately to the bio-based chemical, has significant limitations and results carry considerable uncertainty.

Therefore the specific GHG emissions saving values should be treated with caution. Key areas of uncertainty are the accuracy and alignment of the LCA approaches used to determine fossil fuel counterfactuals, the alignment of LCA methods used across the bio-based chemical studies in respect to allocation methods, the treatment of biogenic carbon across the bio-based chemical studies and transferability of LCA results for studies performed outside of the UK.

Economic impact

Given appropriate support and subject to feedstock availability, the chemical sector has the scale, capacity and transferrable skills necessary to make the UK a leading location for the production of bio-based chemicals and materials on the basis that the UK chemical sector contributes almost £31bn in GVA to the UK economy and accounted for almost one fifth of total UK business R&D expenditure in 2023.

Companies within the serviceable addressable market for bio-based chemicals and materials employ around 130,000 people, generate £60bn in turnover and have invested £680m in R&D.

The UK already as a core of bio-based chemicals and materials activity on which to build. One hundred and nineteen dedicated bio-based chemicals and materials companies identified through this study already generate more than £1bn in turnover and increased their employment base by almost 20% between 2018 and 2022.

Stimulating growth

Growing bio-based chemicals and plastics activity in the UK will require further deep and meaningful engagement with strategically significant companies across the serviceable addressable market. Engagement should focus on:

- Expanding existing bio-based activity among larger dedicated bio-based chemicals companies.
- Supporting high-growth companies to continue improving processes, reducing costs and accessing new markets.
- Engaging with larger diversified bio-based chemicals and materials companies such as to convert more of their UK activity to bio-based.
- Reigniting the start-up bio-based chemicals and plastics ecosystem, ideally with 'buy-in' from existing bio-based market incumbents and / or larger diversified companies.

Requirements and next steps

To promote the development of a bio-based chemical industry in the UK, government support should be utilized in order to encourage the advancement of novel manufacturing processes and the production of new bio-based drop-in chemicals and new-to-market products.

It is clear that further work is needed to develop effective policies that will help to drive the bio-based chemical industry and the wider bio-based economy going forward. Key actions to stimulate growth are described in Figure 2.

Requirements and next steps		
Overarching action	1	UK government to develop a unified cross-departmental biomass utilisation hierarchy and associated joined up policies and regulatory environment that ensures sustainable sourced biomass and biowastes are prioritised for high value materials and products, to derive the maximum value from our bio-resources.
Accelerating the transition to bio-based chemicals	2	Recognition of the benefits of the bioeconomy, and bio-based chemicals, with a dedicated long-term strategy.
	3	Investment frameworks for biomanufacturing of bio-based chemicals, including access to risk capital, enabling multi-scale biorefining facilities.
	4	Innovation principle-applied R&D priorities for bio-based chemicals, digital and AI advancement, intellectual property and innovation protection, plus skills development to support the transition away from fossil resources.
	5	Ensure sustainable government procurement, by implementing a bio-preferred procurement scheme, where the use of bio-based feedstocks is incentivised over fossil-based incumbents.
	6	Remove the Plastic Packaging Tax from certified bio-based packaging materials containing more than 30% bio-based content.
	7	Develop and publish a standardised LCA methodology that considers all the necessary parameters to put bio-based chemicals on a level playing field with their fossil incumbents.
	8	The mass balance approach for bioderived materials should be promoted
	9	Endorse trustworthy certification systems and standards for the sustainable sourcing of biomass feedstocks - clear sustainability criteria and incentives for labels.

Figure 2. Actions to grow the bio-based chemical industry.

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Project Delivered by NNFCC, FREY Consulting, Perspective Economics and Imperial College

February 2024

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By **2050**, the UK bio-based chemicals industry has the potential to significantly grow, producing over

2 million tonnes of bio-based chemicals, contributing to

5.2 million tonnes CO_2eq GHG savings

and **£1.6bn** in value to the UK economy.

1. Introduction

In December 2022 the Department for Energy Security and Net Zero (formerly BEIS) commissioned a 12-month independent study to assess the economic and climate benefits to the UK of an increased use of bio-based chemicals.

NNFCC, FREY Consulting, Perspective Economics and Imperial College London were awarded the project in January 2023, and the study commenced in February 2023.

The study aimed to produce quantitative estimates of carbon savings and economic benefits of various biomanufacturing technologies, to highlight areas in which biomass use in the chemicals sector could best contribute to growing innovation and the economy, while also helping meet the UK's Net Zero ambitions.

The study aimed to answer 3 key questions:

1. Which bio-based chemicals offer the largest potential for Greenhouse Gas (GHG) emission savings relative to their fossil incumbents, either as a like for like replacement, or an alternative product performing the same function?
2. How can the UK's biomass resource can be sustainably, effectively and efficiently processed to bio-based chemicals?
3. What economic benefits could result from the increased production of bio-based chemicals, including the value add over bioenergy application, and the opportunity for the UK to develop a competitive advantage in export markets?

1.1 Methodology

The research methodology consisted of five main strands (1) Project Initiation; (2) Literature Review; (3) Original Research; (4) Quantitative Analysis (Environmental & Economic); and (5) Synthesis and Reporting:

1. **Project Initiation:** A meeting was held with DESNZ in February 2023 at which the research objectives and methodology was agreed. Subsequent project management meetings provided DESNZ with an update regarding progress and methodological amendments.
2. **Literature Review:** On existing and nascent technologies for producing bio-based chemicals and materials, to gain an in-depth understanding of the current status in the UK.
3. **Original Research:** Industry and academic stakeholders were engaged to elicit expert opinion on the UK's current status, opportunities and challenges, and future scenarios.
4. **Quantitative Analysis:** To estimate the potential economic and environmental impacts of bio-based chemicals and materials a quantitative methodology considering several metrics was used.
    - **Environmental analysis** was based on literature review of the life cycle assessment (LCA) associated with the production of bio-based chemicals and materials. The literature search was restricted to a given functional unit i.e., per kg of the target bio-based chemicals identified by the consortium and agreed upon by industry stakeholders. The review enabled us to collect GHG emissions data for bio-based chemicals and their fossil counterfactuals, which was used to determine percentage GHG emissions savings.
    - **Economic analysis** was undertaken using available data to examine current and potential future growth of bio-based chemicals market incumbents at firm-level and to estimate the current economic value of an agreed selection of target chemicals.

5. **Evidence Synthesis and Reporting** stage involved synthesis of quantitative and qualitative evidence to provide clear and systematic responses to each of the research questions, as presented in this report.

1.2 Background and context of the study

The UK manufacture of petrochemicals results in direct GHG emissions of 6.1 million tonnes of CO_2eq per year (average 2012-2021). When the manufacture of all chemicals and chemical derived products (paints, inks, basic pharmaceuticals, rubber, plastics etc) are included, emissions increase to 18.6 million tonnes CO_2eq per year (average 2012-2021)[1].

It is estimated that the global chemical industry currently generates around $4.7 trillion in annual revenue, representing approximately 4% of global GDP, and it is responsible for the employment of over 15 million people worldwide. The global chemical market is expected to grow considerably in the coming years as developing economies continue to advance and society places greater demand on the production of affordable functional materials and products to improve the quality of lives around the world. A growth in demand for petrochemical products will mean that petrochemicals are set to account for over a third of the growth in oil demand by 2030, increasing to almost a half by 2050.

According to BP's "Energy Outlook 2023"*, global oil demand will plateau over the next 10 years or so, before experiencing a steady decline throughout the 2030s and beyond. The single biggest factor driving this decline in oil consumption is believed to be linked to the reduction of gasoline and diesel fuel use in road transport. With gasoline and diesel consumption waning, oil refineries must therefore look to adapt their petrochemical outputs in order to remain economically feasible in the future. Whilst the use of oil in transport is steadily on the decline, the use of oil in petrochemical production still has considerable room to grow. Thus, crude oil to petrochemical technology (crude-to-chemicals) is rapidly becoming the largest driver of worldwide oil demand, and as such, petrochemical applications will soon dominate the global oil industry.

Not only are fossil fuels currently used as the primary feedstocks for the production of petrochemicals, but they are also used to generate the energy, heat and pressure required during the manufacturing processes employed. As a result, industrial chemistry's use of petroleum and natural gas accounts for approximately 6% of all greenhouse gases (GHGs) emitted globally. Therefore, as part of a wider move towards a global economy based on renewable energy, a reduced dependence on fossil resources, and less GHGs emitted to the atmosphere, it is a key aim of the chemical industry to minimise process emissions and to improve the overall sustainability of the sector.

In order to boost the sustainability of chemicals manufacturing, there are a number of changes that can be made to both the products and processes that traditionally depend upon the use of oil and gas. The first of which would be to employ renewable energy in place of fossil-derived fuels during chemical manufacturing processes. The second of which would be to defossilise chemical feedstocks using renewable biomass as an alternative source of carbon. Biomass sequesters carbon from the atmosphere, and this carbon can then be used to make bio-based chemicals. Removing CO_2 from the air, means that any products derived from biomass can potentially have lower associated GHG emissions than their fossil-based counterparts.

In the UK, the chemical industry is the country's second largest manufacturing sector (behind machinery and transport equipment) accounting for over £54bn in exports and £30.7bn in value added to the UK economy in 2021. Despite having experienced covid-19 related lockdowns, severe

1 Office of National Statistics, Residence (production) emissions.
* BP, Energy Outlook, 2023, https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html

trade friction, and soaring raw material prices in recent years, the UK's chemical industry has benefitted from an upsurge in demand for pharmaceuticals and personal care products and was boosted by the stockpiling of goods prior to the end of the Brexit transition period, which further increased the nation's demand for chemicals. As such, the UK's chemical outputs increased by 5.3% in 2020 and by 3.7% in 2021, one of the only industries to experience growth during this period. Since then, elevated energy prices (largely caused by Russia's invasion of Ukraine), coupled with labour and raw material shortages, has led to a general downturn in sector productivity. The most prominent challenge currently facing the UK's chemical sector lies in the current cost of crude oil and natural gas. Unlike other industries, fossil resources are not just utilised as an energy source in the chemicals sector, but also as feedstocks for the production of petrochemicals. This, therefore, intensifies the industry's exposure to any rise in oil and gas prices.

In looking to mitigate the direct and indirect issues caused by high energy and feedstock prices, it is important for the UK's chemical sector to adapt in order to move forward. One way of avoiding these impacts is through the use of renewable energy in place of fossil fuels, and the use of renewable biomass as carbon feedstocks. If the UK chemical industry was to transition to more widespread use of biogenic feedstocks over the use of oil and gas, a sizable amount of biomass would need to be supplied domestically or through imports. Key biogenic feedstocks available in the UK include cereal crops (e.g., wheat, barley, oats, oil seed rape) & cereal crop residues, sugar beet & sugar beet pulp, forestry biomass & forestry residues, perennial ryegrass, macroalgae, and industry wastes/residues (e.g., paper waste, distillery wastes, and bread manufacturing waste).

1.3 Study limitations

Key study limitations include:

Environmental Analysis: There are significant limitations to applying LCA in assessing environmental impact of bio-based chemicals. The accuracy of an LCA study depends on the quality and availability of relevant data. It was impossible to conduct a bottom-up assessment due to a lack of data from industry stakeholders, given its proprietary nature. Estimations and inclusion or exclusion of 'biogenic carbon' claims in LCA studies, has significant influence on results. There is still no clear consensus in literature and among practitioners on how to deal with this aspect with respect to LCA impact assessment. The majority of LCA on bio-based chemicals and materials, does not include indirect land use change (ILUC) mostly due to the modelling complexity, the uncertainty related to its assessment and the disagreement among experts about how to allocate the resulting impacts. The scientific community agrees that ILUC needs to be evaluated within LCA approaches, but the lack of a consistent framework remains a challenge. The large variation in considered impacts and life cycle stages across LCA studies reflects current challenges and limitations when assessing bio-based chemicals. Each studied system is unique in features and components, rendering it difficult to compare it with functionally equivalent systems or processes. It was evident from literature reviewed that inconsistent application of well-defined guidelines can yield highly variable LCA results even when the same impact categories are assessed. Most of the papers that have been reviewed in this study have taken the conventional LCA approach which is static without temporal and spatial variations. However, systematic analysis of spatiotemporal dynamic variations and comprehensive operable dynamic models are still lacking in LCA generally. We recommend that future studies follow Product Environmental Footprint (PEF) guidelines or the ISO 14040 standards series particularly the specific standard EN 16760:2015 for guidance concerning the general LCA methodology on modelling of agriculture, forestry and aquaculture systems, which are recognized to have relevant environmental impacts in bio-based production systems.

Economic Analysis: The methods used to estimate bio-based chemicals and materials economic activity in this study are experimental. They do not use traditional Standard Industrial Classification

(SIC) codes and are therefore not consistent with formal economic statistics produced by the Office for National Statistics, the Chemicals Industry Association, or other central government departments. Specifically, the analyses presented in this report use novel approaches to estimate the proportion of bio-based activity within chemicals and materials companies using web-based employment data.

2. Stakeholder Engagement

Stakeholder engagement was considered critical in ensuring that the study focused on UK relevant bio-based chemical potential (see section 4.1). Stakeholders were engaged via several activities throughout the study.

- Online Survey - https://www.surveymonkey.co.uk/r/5QF5F85
- 1:1 Interviews – held online between February and May 2023.
- Validation workshop 1: June 26th 2023, where the top 15 biochemicals were presented to stakeholders.
- Validation workshop 2: November 7th 2023, where the results of stakeholder analysis, literature review and quantitative analysis were presented to key stakeholders for validation.

Stakeholders consulted during the study included large, medium and small businesses, government officials, academics, banks and trade bodies. In total the study has engaged with 69 individual organisations. 50 organisations completed the survey, and 50 organisations were interviewed, covering TRLs 1 to 9.

Organisations were from a variety of sectors including speciality chemicals, plastics, fibres, chemicals, biotechnology, consumer products, commodity chemicals, paper and coatings, bio-based chemicals and materials, composites, agrochemicals, bioplastics, agriculture, circular economy and pharmaceuticals (See Annex 2).

Information gathered through the survey and interviews included:

- Company information,
- Company Net Zero, Decarbonisation, Defossilisation targets,
- Chemicals / bio-based chemicals produced today and volumes,
- Bio-based chemicals that are imported,
- Bio-based chemicals that are important for the future,
- Feedstocks used and carbon footprints of products,
- Current technologies used and state of technology and innovation to transition to biochemical production,
- Appetite of industry to transition, and barriers to transitioning to biochemicals and materials,
- Economic information,
- Potential future manufacturing scenarios,

3. Economic and climate benefits to the UK of an increased use of bio-based chemicals

3.1 Significance of chemicals and materials activity to the UK economy

The chemicals and materials sector is a vital component of the UK economy. In 2023, the Chemicals Industry Association (CIA) used Standard Industrial Classification (SIC) codes to estimate that there were 4,415 chemicals businesses in the UK. In 2023, these businesses:

- Employed approximately 151,000 people.
- Contributed an estimated £31bn in Gross Value Added (GVA) – equivalent to almost one sixth of all UK manufacturing GVA.
- Exported approximately £54bn of manufactured goods.
- Were responsible for around one sixth of total UK business R&D expenditure.

Given the significant contribution of the current chemicals and materials sector to the UK economy, it is clear that:

a) converting even a fraction of that activity to become bio-based could offer considerable economic opportunity, and that;
b) the talent and skills required to grow bio-based chemicals and materials activity exist in the UK.

3.2 Current challenges for the commercialisation of bio-based chemicals

Stakeholders were asked what the most significant barriers their organisations, and/or the sectors, are facing in the expansion of, or switching to, bio-based chemical production (Figure 1).

Stakeholders agreed that the production and widespread adoption of bio-based chemicals face several barriers that can hinder their development and implementation.

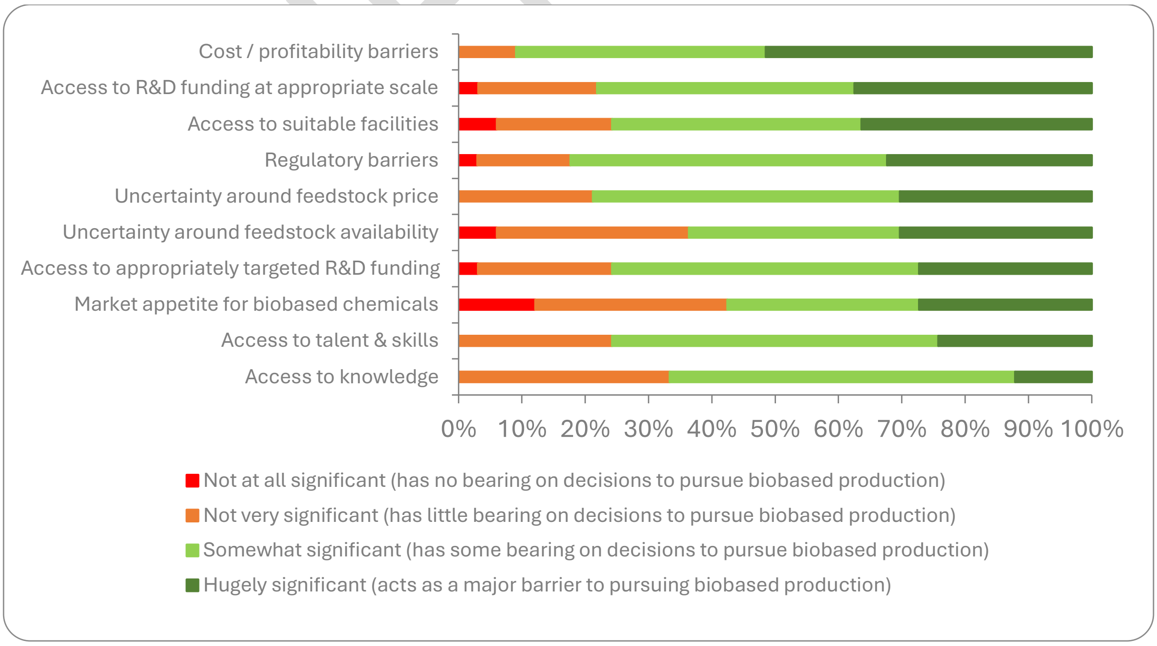

Figure 1. Stakeholder views on challenges in bio-based chemical commercialisation.

Some of the significant barriers include:

Cost/Profitability: The greatest barrier to transitioning is perceived to be economics. Bio-based chemicals often face cost competitiveness challenges when compared to their fossil-based counterparts. High capital investment costs, limited economies of scale, and the dependency on fluctuating feedstock prices can make bio-based chemical production economically unviable. Achieving cost parity or cost advantage is crucial for their commercialisation and widespread adoption. Since businesses work on short (1-3 year) business plans, where profit is the main KPI, reduced profits are not usually accepted by shareholders.

Feedstock Availability and Price: Bio-based chemicals are derived from renewable resources such as plants, agricultural waste, or algae. The availability and consistent supply of these feedstocks can be a challenge. Factors such as land availability, climate variability, and competing uses (e.g., food production) can limit the availability of feedstocks and impact the scalability of bio-based chemical production. Access to consistent feedstocks, at the required volume, required specification, and consistent cost, alongside understanding future feedstock availability was also highlighted as a key barrier.

All stakeholders highlighted the issue of ensuring that the uptake of using a certain biomass did not replace its usage elsewhere, leading to overall less sustainable practices. One example described was the use of animal fat to produce jet fuel, where airlines are under pressure to reduce their carbon emissions, which mainly come from burning fossil-based kerosene in aircraft engines. Demand for fuel made from biomass or derived from animal by-products is expected to triple by 2030. But experts fear scarcity will force other industries to use more palm oil – potentially a significant generator of carbon emissions. A second example was distillery by-products, traditionally used as an animal feed, being diverted to produce bio-based chemicals, leading to farmers importing soy from Brazil, which generates significantly more carbon emissions.

Technological Challenges: The conversion of biomass into bio-based chemicals often involves complex and resource-intensive processes. Developing efficient and cost-effective technologies for biomass pretreatment, enzymatic hydrolysis, fermentation, and chemical conversion poses technical challenges. Optimisation of these processes, as well as improving the yield and selectivity of target chemicals, requires ongoing research and development efforts. As mentioned above, there was an overwhelmingly unanimous response that the technologies required to transition to bio-based chemicals are not at high enough TRLs for industry to adopt them.

Infrastructure, Energy and Logistics: The existing infrastructure for the production, storage, and transportation of chemicals is typically designed for fossil-based chemicals. Establishing a dedicated infrastructure for bio-based chemical production, including feedstock collection, processing facilities, and distribution networks, requires significant investment. In addition, the significant investment in existing assets, which utilise fossil resources, means that organisations want to utilise these as much as possible, before making any new investments. The conversion of biomass into bio-based chemicals often involves resource-intensive processes, and so access to cheap renewable and low-carbon energy was highlighted as being essential for the transition away from fossil resources.

Access to Scale-up Facilities: Many stakeholders cited the need for UK pilot and demonstration facilities to be available to help scale up technologies and processes, alongside the need for subsidised access to such facilities for SMEs. Many organisations are currently having to take their processes to Europe to carry out scale-up.

Access to Finance: The need for long-term access to finance was seen as an issue by most stakeholders, spanning the full TRL. Several stakeholders noted that the lack of longevity of funding meant that lots of innovative projects get to TRL 3 or 4 but never any further. It was also noted that for SMEs that Innovate UK funding was inaccessible for some due to the need for them to fund 30%

of costs themselves and have sufficient cash reserves to undertake the project prior to the grant being paid. In terms of investment, stakeholders felt that the UK does not support start-ups in the bio-based chemicals sector, and that most investment is from abroad. For example, Holiferm has secured most of its investment from the US and EU. One stakeholder cited that Sanofi, one of the largest investors in the bio-based chemicals space, has not made an investment in the UK since Brexit.

Policy and Regulation: Policy frameworks and regulations play a crucial role in shaping the market for bio-based chemicals. Inconsistent or unclear regulations, lack of supportive policies, and limited financial incentives were seen to hinder investment and impede market growth. Stakeholders believe that well-defined policies that encourage the use of bio-based chemicals, provide incentives, and address potential environmental and social impacts are essential in creating a favourable environment for their adoption. One particular issue that was highlighted by stakeholders was that new products manufactured from biomass need to have the same, or better performance than their fossil resource counterparts, which requires requalification of specification – which is extremely costly. Many stakeholders also noted that fees to register a new chemical product with REACH could span into the millions, making the bio-based products development unviable.

Market Acceptance: Stakeholders noted that bio-based chemicals often face challenges in gaining market acceptance due to various factors, including cost differences, limited awareness among consumers, potential performance gaps compared to conventional chemicals, and resistance from established industries. Stakeholders felt that demonstrating the performance, safety, and sustainability benefits of bio-based chemicals and educating consumers and industries about their advantages is crucial for market acceptance and demand creation.

Access to Expertise: SMEs in particular noted that gaining access to academic expertise was difficult, and finding out where expertise is available was hard – not knowing which researchers or institutions specialize in the areas relevant to their needs. Industry also had concerns about intellectual property (IP) and ownership when collaborating with academia.

Skills Shortages: Despite the UK's strength in chemical processing, several stakeholders noted the UK has a skills gap in biochemical engineers who could translate chemical processes into bio-based ones. There is a need for individuals with strong technical skills in biochemical engineering processes, including knowledge of bioreactor design and operation, fermentation, downstream processing, and process optimization. The application of advanced technologies, such as computational modelling and data analysis, also requires specialized expertise. A skills gap around LCA was also noted. For example, Holiferm cited that they have struggled to find the skilled workforce they need and are having to spend increasing amounts on visa fees to bring in talent from abroad.

Social Impact: There was a perception amongst stakeholders that the public did not consider climate change as an immediate threat, and that the UK was going to be able to mitigate any effects. Stakeholder felt that addressing these barriers requires a multi-faceted approach involving collaboration among industry, academia, policymakers, and research institutions. Investments into public awareness campaigns are vital for overcoming these barriers and promoting the widespread adoption of bio-based chemicals.

Brexit: many stakeholders cited Brexit and not being able to access EU funding for a timeframe has led to a drop in UK bio-based chemicals sector growth.

4. Future Scenarios

4.1 Selection of target bio-based chemicals

In order to be able to study environmental and economic impacts from bio-based chemical production a sample of bio-based chemicals which could be assessed within the scope of the study was required.

A literature review, alongside an online survey (https://www.surveymonkey.co.uk/r/5QF5F85), was used to compile a long list of potential bio-based chemical targets which could potentially be produced in the UK (Table 6).

Table 1. Long list of potential bio-based chemical targets which could potentially be produced in the UK.

Carbon Dioxide	Furandicarboxylic Acid (2,5-)/HMF/	Lignin
3-Hydroxybutryolactone	Furfural	Lysine
Acetaldehyde	Glucaric Acid	Malic Acid
Acetic Acid/Anhydride	Gluconic Acid	Malonic Acid
Acetoin	Glucose	Methanol
Acetone	Glutamic Acid	Methyl methacrylate
Aconitic Acid	Glutaric Acid	Muconic Acid
Alanine	Glycerol/Glycerin	Oxalic Acid
Ascorbic	Glycine	Pelargonic Acid
Aspartic Acid	hemicellulose sugars - galactose	p-menthane 3,8 diol
Azelaic acid	hemicellulose sugars - mannose	Proline
Butanediol (1,4-)	Hemicellulose sugars - xylose	Propane (1,3-)
Butanol (n-)	Hydrocarbons	Propionic Acid
Carbon Monoxide	Hydrogen	Propylene Glycol
Cellulose	Hydroquinone	Serine
Citric Acid	Hydroxybutyrolactone (3-)	Simple sugars
Ethanol	Hydroxypropionic Acid (3-)	Sodium Alginate
Ethylene	Isoprene	Sorbitol
Ethylene Glycol/Oxide	Itaconic Acid	Succinic Acid (1,4-)
Fatty Alcohols	Kojic and Comeric acid	Threonine
Formic Acid	Lactic Acid/Ethyl Lactate	Xylene
Fructose	Levoglucosenone	Xylitol/Arabitol
Fumaric Acid	Levulinic Acid	

To reduce the long-list down to a manageable list of bio-based chemicals, stakeholders were engaged via several activities:

- 1:1 Interviews – held online between February and May 2023
- Validation workshop 1: June 26th 2023, where the top 15 bio- based chemicals were presented to stakeholders

Based on all information gathered through stakeholder engagement, a shorter list of bio-based chemicals was produced through a red, amber, green (RAG) rating exercise. For the study the project team wished to assess bio-based chemicals of relevance to the UK, economically, with respect to Net Zero impacts and in terms of industry activities, irrespective of whether other chemicals may deliver greater impacts globally. Therefore the RAG rating was based on three criteria covering achievability, plausibility and impact:

- **CREDIBLE/ACHIEVABLE** – the feedstock and production technologies are available (commercial/demonstration now for 2030 horizon, demonstration/pilot now for 2040 horizon and lab now for 2050 horizon).
- **MEANINGFUL** – production/demand would be at a scale sufficient to make a meaningful carbon savings impact.
- **PLAUSABLE/REALISTIC** – There is clear UK interest in the production or use of the chemical (ideally a UK chemical company producing/using or looking to produce/use).

Infrastructure, demand and integration were also incorporated by considering where bio-based chemical production might fit with current activity and infrastructure, reviewing chemical import data to understand downstream industry needs, and incorporating stakeholder insights.

Several concepts for the production of bio-based chemicals and materials can be envisaged:

1) Biorefinery
2) Distributed biomanufacturing
3) Business as usual, with mass balance approach

For concepts 1 or 2 any of the key process technologies could be employed, for concept 3 the biomass or a derived intermediate must be suitable for processing alongside fossil feedstock using the existing processes and infrastructure.

Concept 1 - Large scale production of multiple products within biorefineries

Biorefineries benefit from economies of scale and the potential to optimise energy and product streams. Biorefineries aim to utilise all feedstock components, therefore minimising residue streams requiring processing off-site. The UK's two world scale ethanol plants are biorefineries producing ethanol currently sold as transport fuel, animal feed and one refinery also produces food grade carbon dioxide.

Concept 2 - Single product focussed production within distributed biomanufacturing facilities

Not all bio-based chemical production will necessarily take place in large scale biorefineries. Production scales may be determined by feedstock availability, product market size of offtake potential, or access to financial capital. For these reasons bio-based production may occur at smaller facilities termed in this report as biofactories. It may also be the case that for novel products or processes, initial production takes place in biofactories, but as production scales up, facilities evolve into biorefineries. An example of where this could happen would be when a process initially based on refined fermentable sugar scales and transitions to unrefined feedstock such as cereal grain or lignocellulosic biomass.

Concept 3 – Co-processing of biomass and fossil resources within existing petrochemical complexes

In both concepts 1 and 2, capital investment is required to build new or repurpose old facilities and infrastructure. A lack of financial capital is often a barrier to the installation of new bio-based chemical production capacity. As a result the concept of co-processing biomass with fossil feedstock, taking advantage of existing production assets without the need for significant capital investment, is seen as an attractive approach to increase the use of biomass as sustainable feedstock for the chemical industry. A drawback of co-processing is relative scales of petrochemical processing and biomass availability. The volumes of biomass co-processed with fossil feedstock are typically small and therefore the biogenic (bio-based) content of any of the products produced is equally small, negatively impacting its commercial attractiveness. To overcome this issue mass balance accounting has evolved. Under mass balancing methods the amount of biomass being co-processed can be attributed to a single product or batch of product allowing it to be sold as 100% bio-attributed.

The conversion of biomass feedstock to bio-based chemicals and materials can be achieved through a wide range of technologies. Key technologies include thermochemical processes such as pyrolysis, gasification and hydrothermal reforming, chemical transformations including hydrolysis and reduction, and biotechnologies e.g., fermentation and anaerobic digestion. These key technologies are often preceded by mechanical process such as crushing, chipping, grinding and drying.

The preferred technology is often determined by the type of feedstock to be processed. Feedstock with high moisture content is suited to biotechnologies and hydrothermal processes, whereas drier feedstocks suit thermochemical processes.

The UK chemical industry employs a broad range of thermochemical and chemical processes, but the use of biotechnology in chemical production to date has been limited. The exception to this is the production of bioethanol based on the fermentation of sugars derived from wheat and other starch crops. The UK has the capacity to produce over 650,000 tonnes of ethanol via fermentation.

Table 2. Future scenarios for bio-based chemical and materials.

	Manufacturing option		
Potential bio-based chemical/material	**Biorefinery**	**Distributed Manufacturing**	**Business as usual***
	LACTIC ACID via fermentation for solvent and polymer production	**BUTANOL, ACETONE AND ETHANOL** via ABE fermentation for solvent applications	**BIO-BASED PROPANE** from SAF production as feedstock for crackers (ethylene, propylene etc)
	MONOETHYLENE GLYCOL via sugar hydrolysis for polymer and surfactant production	**BIOSURFACTANT** via fermentation for solvent applications	**BIO-BASED NAPHTHA** from SAF production as feedstock for crackers (ethylene, propylene etc)
	ETHYL ACETATE via ethanol for solvent applications	**FURANDICARBOXYLIC ACID (AND HMF)** via sugar chemistry for surfactant and polymer production	**BIO-BASED METHANE (BIOMETHANE)** as feedstock for acetic acid, acetic anhydride and ethyl acetate production.
	ETHYLENE via ethanol for polymer production	**BUTANEDIOL** via fermentation for polymer production	
	METHYL METHACRYLATE via fermentation for polymer production	**SUCCINIC ACID** via fermentation for polymer production	
	METHANOL from green hydrogen and CO_2 off gas	**DIHYDROLEVOGLUCOSENONE** via sugar chemistry as a novel solvent	

*Most likely mass balance approach

Table 3. RAG assessment of 15 potential bio-based chemicals and their potential to have an economic and environmental impact.

Chemical Target	Credible /Achievable (technology & commercial readiness, TRL and CRI)	Meaningful (potential impact)	Plausible/Realistic (relative potential)
Lactic Acid as PLA (from biogenic MSW)	TRL 8/CRI 1	Production potential >100,000tonnes	Strong interest from potential UK producer
Monoethylene glycol (from cellulosic sugar)	TRL 9/CRI 2	Production potential >100,000tonnes	Interest from UK value chain.
Ethyl Acetate (from ethanol)	TRL 9/CRI 2	Production potential >100,000tonnes	Strong interest from non-UK company with UK assets
Ethylene (from ethanol)	TRL 9/CRI 3	Production potential >100,000tonnes	Interest from non-UK company with UK assets
Methyl methacrylate (from starch/sucrose sugar)	TRL 4-5/CRI 1	Production potential >100,000tonnes	Supported by multi-national with global view
Methanol (from CO_2)	TRL 9/CRI 1	Production potential >100,000tonnes	Interest from potential UK producer
Butanol/Acetone/Ethanol (from agri-food by-products)	TRL 9/CRI 2	Production potential >10,000tonnes	UK technology and producer
Biosurfactant (from starch/sucrose)	TRL 9/CRI 2	Production potential >10,000tonnes	UK technology and producer
Furandicarboxylic acid (from cellulosic sugar)	TRL 7-8/CRI 1	Production potential >10,000tonnes	Interest from value chain.
1,4-Butanediol (from starch/sucrose)	TRL 9/CRI 3	Production potential >10,000tonnes	Interest from value chain.
Succinic acid (from starch/sucrose)	TRL9/CRI 2	Production potential >10,000tonnes	Interest from value chain.
Dihydrolevoglucosenone, Cyrene™ (from lignocellulose)	TRL 8/CRI 1	Production potential >10,000tonnes	Interest from non-UK company with UK research interest and potential interest in UK production.
Ethylene/Propylene (from bio-based propane)	TRL9/CRI 3	Limited	UK interest in propane could not be determined.
Acetic acid (from biomethane)	TRL 9/CRI 1	Production potential >100,000tonnes	UK based production of feedstock and product
Ethylene (from bio-based naphtha)	TRL9/CRI 3	The switch from liquid to gas crackers means the UK no longer has the capability to process liquid naphtha feedstock	

Based on the results of the RAG rating, pathways relating to the use of co-products generated during the production of renewable diesel and sustainable aviation fuel (SAF) were removed from further analysis. These processes produce varying amounts of propane and naphtha which can serve as feedstocks for petrochemical steam crackers. However, there is significant uncertainty around the volume of propane that could become available based on UK production and due to the conversion of the UK's naphtha-based steam crackers to gas (ethane) feedstocks, the UK no longer has the capability to process naphtha. Based on this understanding it was decided that these pathways did not meet the selection criteria described earlier.

Of the fifteen bio-based chemical targets originally identified, five are commercial processes, six are semi or near commercial with demonstrated technology, three are pre commercial with processes being demonstrated and one is in technical development.

Within the reduced list of thirteen target bio-based chemicals (i.e., minus SAF by-product derivatives), three are commercial processes, six are semi or near commercial with demonstrated technology, three are pre commercial with processes being demonstrated and one is in technical development. Although not commercially practiced, bio-attributed acetic acid could be readily commercialised if commercial requirements around the price of biomethane could be achieved.

These scenarios were presented at a workshop on Monday 26th June 2023, attended by over 65 stakeholders and validated as reasonable potential future scenarios.

Following on from this, quantitative analysis of the 13 potential bio-based chemicals and associated production pathways was undertaken and presented at a second validation workshop on November 7th 2023, where barriers to a transition to these were discussed, alongside how the transition could be accelerated.

4.2 Feedstock Considerations

Modelling the future availability of biomass supply is challenging and inherently uncertain. Biomass supply is determined by a range of technoeconomic, market demand and political/policy factors which can stimulate supply, create market competition or restrict supply based on sustainability considerations.

Modelling underpinning the Biomass Strategy suggests that the total potential sustainable biomass estimated to be available for UK use is highly uncertain. Scenario modelling resulted in estimates of availability with values of 550-750 PJ in 2025 and 500-1,000 PJ in 2050. However, the variation in potential results from assumptions of the availability of sustainable biomass for import into the UK. The availability of domestic biomass remained relatively stable in the region of 370-390 PJ in 2050 across restricted and ambitious supply scenarios.

The importation of biomass for bioenergy purposes can be justified on the basis that electricity and heat distribution is limited by distance (electricity interconnecters are 100's of kms in length) and therefore biomass is imported to generate electricity closer to where it is required. In regard to bio-based chemical products, producers have a choice, to ship biomass to a distant chemical plant for processing or process the biomass at source and ship a refined intermediate or product. While the shipping of some biomass feedstock e.g., vegetable oils and cereal grains for chemical processing is common, most biomass is considered difficult to transport due its low density. Therefore with the exception of the examples cited, biomass is assumed to be processed at source and the study only considers domestic UK feedstock supply. There is one exception to this rule. The solvent dihydrolevoglucosenone is produced via pyrolysis and is co-produced as a minor product with large quantities of biochar. Biochar is an effective fuel product and suitable for use in bioenergy applications. Therefore, it was considered reasonable that dihydrolevoglucosenone could be produced using imported biomass with the produced biochar being returned to the bioenergy value chain.

Each target chemical could be produced though a variety of feedstocks. For example, ethanol is currently produced from arable crops (i.e., wheat and sugar beet). However it could be produced from lignocellulosic biomass resources, or from various agri-food process residues.

Based on stakeholder engagement it was evident that a certain feedstock is more likely to be used for the production of a specific chemical. An overview of this potential feedstock to bio-based chemical relationship is shown in Figure 2.

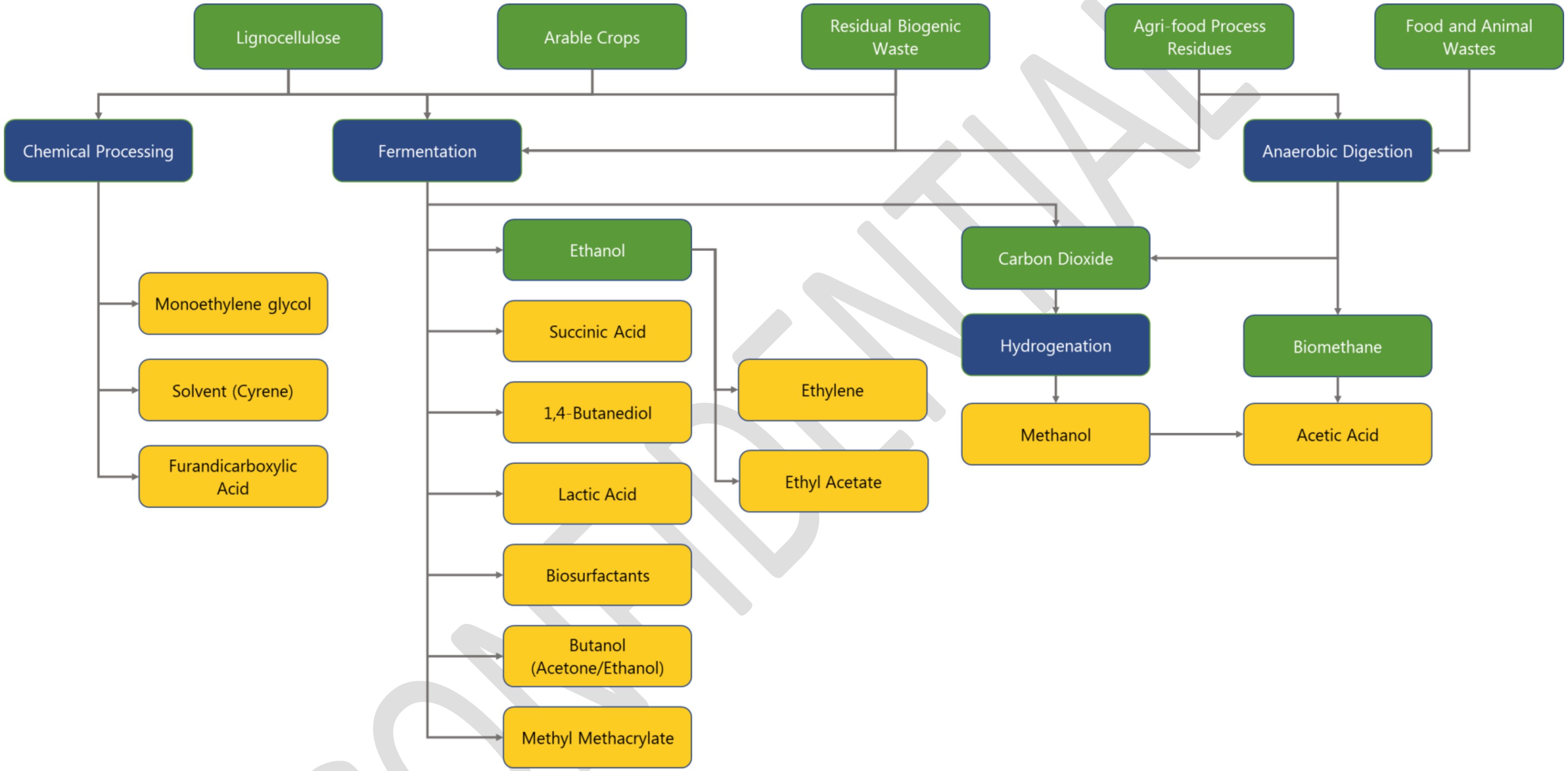

Figure 2. UK feedstock to bio-based chemical relationship

A breakdown of feedstock requirements for nominal volumes of target bio-based chemicals and how the required volumes relate to the volume of available feedstock is provided in Table 9.

Table 4. Feedstock requirements for nominal volumes of target bio-based chemicals (For established arable crops, volumes are taken for current production which is considered a conservative estimate of 2050 availability).

Chemical	Production (tonnes)	Feedstock type (volume tonnes)	Percentage of feedstock availability
Lactic Acid	100,000	Biogenic fraction of MSW (350,000)	13% (based on 2050 Biomass Strategy projections)
Monoethylene glycol	100,000	Forest products and residues (425,000)	7% (based on 2050 Biomass Strategy projections)
Ethyl Acetate	100,000	Existing UK ethanol production (380,000)	17% (based on wheat to feed current ethanol capacity)
Ethylene	100,000	Existing UK ethanol production (565,000)	26% (based on wheat to feed current ethanol capacity)
Methyl methacrylate	100,000	1) Agricultural field residues (935,000) 2) Biomass crop (772,000)	1) 108% (based on 2050 Biomass Strategy projections) 2) 39% (based on 2050 Biomass Strategy projections)[2]
Methanol	100,000	Biogenic carbon dioxide (ex bioethanol and biomethane production) (140,000)	28% (based on existing bioethanol capacity)
Butanol/Acetone/Ethanol	50,000	Agri-food process residues (125,000 tonnes of fermentable carbohydrate).	24% (based on 2050 Biomass Strategy projections, assumes 40% fermentable carbohydrate)
Biosurfactant	50,000	Sugar (ex wheat grain or sugar beet) 27,000	2% (based on current UK annual sucrose production)
Furandicarboxylic acid	50,000	Forest products and residues (207,000)	3% (based on 2050 Biomass Strategy projections)
1,4-Butanediol	50,000	Sugar (ex wheat grain or sugar beet) (100,000)	8% (based on current UK annual sucrose production)
Succinic acid	50,000	Sugar (ex wheat grain or sugar beet) (75,000)	6% (based on current UK annual sucrose production)
Dihydrolevoglucosenone	50,000	Imported biomass pellets (1,000,000)	11% (based on current imports)
Acetic acid (47% bio-based)	100,000	Biomethane (0.43TWh)	7% (based on current grid injection). 2% (based on 2050 grid injection of 30TWh)

4.3 Chemical production scenario

To enable the assessment of economic and environmental impacts resulting from an increase in bio-based chemical and materials production a scenario for production of the thirteen target bio-based chemicals from the chosen feedstock across the 2030, 2040 and 2050 timeframes was created. The scenario builds on the following hypothesis.

Chemicals with pathways at technology readiness level (TRL) 8 and commercial readiness index (CRI) 1 or above, also having a strong UK stakeholder association are deployed by 2030, biorefinery and bio-attributed chemicals are produced at 50,000 tonnes and distributed biomanufacturing chemicals are produced at 10,000 tonnes.

By 2040, all target chemicals are produced in the UK, the production of ethyl acetate from ethanol has scaled from 50,000 tonnes to 100,000 tonnes and ethylene is produced at 200,000 tonnes (representing the full capacity of one UK wheat ethanol plant dedicated to ethylene production). Lactic acid production has scaled from 10,000 tonnes to 50,000 tonnes and both methyl methacrylate and methanol are produced at initial volumes of 10,000 tonnes. Distributed

[2] Note: Biomass Crop volume projections out to 2050 are uncertain and dependent on Government policy actions, availability could be around 13 million tonnes compared to the 2 million tonnes used as the basis of availability.

biomanufacturing chemicals commercially established by 2030 increase in scale from 10,000 tonnes to 50,000 tonnes. Production of bio-attributed acetic acid grows from 50,000 tonnes to 200,000 tonnes as biomethane availability grows.

By 2050, all bio-based chemical production has been scaled. Production of ethyl acetate and ethylene consume one hundred percent of UK ethanol production. Other biorefinery chemicals are produced at 100,000 tonnes with the exception of monoethylene glycol which takes advantage of the volume of forest feedstock to reach 200,000 tonnes of production. Of the original distributed biomanufacturing chemicals, butanol production is practised at multiple sites with a production volume of 50,000 tonnes and biosurfactant production has scaled to 100,000 tonnes. Dihydrolevoglucosenone has scaled to 200,000 tonnes of production taking advantage of the UK's import of biomass for electricity production with carbon capture (BECCS). Other distributed chemicals scale from 10,000 tonnes to 50,000 tonnes. Acetic acid production utilises biomethane, fully replacing the use of natural gas as a chemical feedstock.

The resulting production volumes are shown in Figure 3 and Table 10.

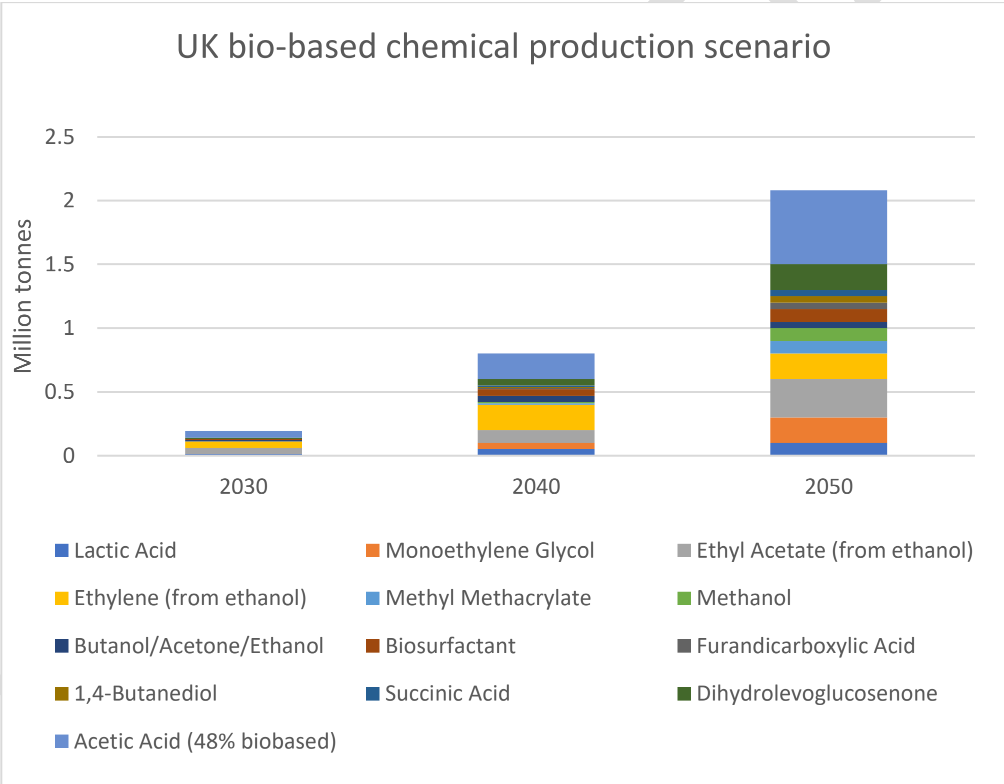

Figure 3. Bio-based chemical production scenario (2030, 2040, 2050)

Table 5. Bio-based chemical production scenario (2030, 2040, 2050)

		Production Million Tonnes		
	TRL/CRI	2030	2040	2050
Lactic Acid	8/1	0.01	0.05	0.1
Monoethylene Glycol	9/2	0	0.05	0.2
Ethyl Acetate (from ethanol)	9/2	0.05	0.1	0.3
Ethylene (from ethanol)	9/3	0.05	0.2	0.2
Methyl Methacrylate	4-5/1	0	0.01	0.1
Methanol	9/1	0	0.01	0.1
Butanol/Acetone/Ethanol	9/2	0.01	0.05	0.05
Biosurfactant	9/2	0.01	0.05	0.1
Furandicarboxylic Acid	7-8/1	0	0.01	0.05
1,4-Butanediol	9/3	0	0.01	0.05
Succinic Acid	9/2	0	0.01	0.05
Dihydrolevoglucosenone	8/1	0.01	0.05	0.2
Acetic Acid (48% biobased)	9/1	0.05	0.2	0.58
Total		0.19	0.80	2.08

At a second validation workshop on November 7th, 2023, results of stakeholder analysis, literature review and quantitative analysis were presented to key stakeholders for validation.

5. Environmental impact of bio-based chemicals

This section presents findings from analysis of the potential environmental benefits of bio-based chemicals and materials production (from more details see Annex 5).

Producing bio-based chemicals from renewable resources is a major driver for moving towards sustainable societies. Renewable resources of biological origin offer the UK chemical industry an opportunity to diversify its feedstocks and to produce bio-based chemical products. This will help modernize and strengthen the UK's industrial base, creating new greener value chains and potentially cost-effective industrial processes, whilst safeguarding the environment.

Life cycle assessment (LCA) is a standardized tool used to measure related progress by quantifying environmental sustainability performance of chemical products along their life cycles. LCA aims at capturing all relevant environmental impacts occurring along full product life cycles from raw material extraction, manufacturing to end-of-life, and helps pinpointing hotspots in production stages and processes. LCA has evolved into a major decision support tool for environmental sustainability assessment related issues, including assessing the emissions reductions of bio-based chemicals in comparison to their fossil sources.

Many companies use LCA to demonstrate transparency and corporate credibility to stakeholders and customers. LCA is also used in new product research and development when environmental footprint is important to the future marketing or cost structure of a product. LCA is increasingly recognized in business rationales as consumer and regulatory environmental expectations are increasing in demand and sophistication.

However, as a decision support tool the quality of the answer that LCA provides is in part determined by the framing of the questions to be answered. The question being asked determines how the LCA is performed and what choices on method the LCA practitioner makes. This specificity of the LCA approach to the question being asked, makes comparing results from different LCA studies challenging.

5.1 Approach

Quantitative analyses of the environmental impacts related to bio-based chemicals and materials produced are relatively scarce and fragmented. Usually, environmental results are published in the form of academic and industry research case studies.

A search of the peer review literature and other published sources was undertaken to determine what the global warming potentials (GWP) impact of bio-based chemicals was, compared to the fossil-derived equivalent chemicals. Most of the results obtained in literature are based on a cradle-to-gate system boundaries, but a few are for cradle-to-grave.

In a previous study undertaken on behalf of the Department for Energy and Climate and Change, the National Non-Food Crops Centre commissioned North Energy Associates (NEA) Ltd to undertake LCA of five major bio-based chemicals. The NEA LCA spreadsheet models covered 1,4 butanediol (BDO), acrylic acid, butanol, linear low-density polyethylene (LLDPE) and polylactic acid (PLA) from sugar beet and wheat grain. These models were reviewed and key emission factors and GWP were updated. The updated outputs of these models are included Annex 5.

In addition, a data requirement sheet was circulated to key stakeholders with the aim of collecting primary data for bottom up LCA studies. However, it was not possible to obtain detailed data from the majority of stakeholder companies, either data was unavailable or considered too commercially sensitive to share. The industry data would have helped in updating some of the data in the NEA models.

However, some companies were willing to share LCA and sustainability reports which we used to supplement GHG emission data obtained from the literature review. These data were used to develop a metric to determine the GHG emissions savings for the targeted chemical.

It is reasonable to assume that across the study time frame the efficiency of bio-based chemical production will increase based on a combination of technical breakthroughs and learning through doing. Given the relative low maturity of bio-based chemical production compared to fossil chemicals it can be anticipated that improvements (yield improvements and energy requirements) to bio-based chemical production will outpace those made for fossil based production. Additionally, the production of bio-based chemicals typically has larger energy requirements than fossil counterparts and therefore GHG emission reductions resulting from the decarbonation of heat and power production will have a larger impact on bio-based production relative to fossil chemicals.

However due to the uncertainties around process development the potential for increased relative GHG emission savings from an increase in renewable energy used in production has not been factored into the results presented in this report.

End-of life treatment has a significant impact on the full life cycle GHG emissions of chemicals and materials. Whether a material is sent to landfill, incinerated or recycled determines whether carbon embodied within the material is sequestered or released to the atmosphere as carbon dioxide. For the purpose of this study it was assumed that the end-of-life fate of bio-based and fossil materials would be identical and would therefore not affect relative GHG emissions savings.

5.2 Key findings

Generally, the climate change impact of bio-based chemicals is lower compared to those made from fossil feedstocks. The percentage GHG emissions change across all studies reviewed ranged from an emission increase of 681% (biosurfactant) to a saving of 300% (methanol). Emission savings of greater than 100% reflect the comparison of bio-based and fossil emissions at factory gate, where the bio-based chemical has negative emissions resulting from sequestration of carbon dioxide in the chemical. Across the studies regarded as most relevant to the UK and the production scenarios considered in this report, GHG emissions savings range from 5% (methyl methacrylate) to 95% (methanol).

Literature findings for a selection of individual bio-based chemicals are described below and the target chemical GHG saving used in the scenario analysed are presented in Table 11.

- It can be estimated from the literature reviewed that bio-based ethylene (via ethanol) produced from fermentation of wheat and sugar beet has a potential GHG emission saving ranging from 65% to 72% in comparison to the fossil counterfactual.
- Similarly, GHG saving ranging from 27% to 51% could potentially be achieved by producing bio-based 1,4-butanediol from wheat and sugar beet.
- Production of polybutylene adipate terephthalate (PBAT) using UK wheat straw showed a potential GHG emission saving of 74%.
- Bio-based butanol produced from sugar beet and wheat feedstocks had a GHG saving of between 36% and 97% depending on the choice of feedstock used.
- Production of bio-based high-density polyethylene (HDPE) using UK wheat straw as the feedstock demonstrated a potential GHG emission saving of 205%.
- The highest GHG emission saving (95%) arises from producing methanol from a mixture of CO_2 from flue gas and hydrogen from water hydrolysis.
- Bio-based polylactic acid produced via fermentation using UK wheat demonstrated a potential GHG emission saving of between 20% to 80% depending on allocation measures considered.

- A range of 32% to 41% GHG emission saving was observed for succinic acid produced through fermentation of UK wheat and sugar beet, although higher GHG saving of between 40% to 91% were observed for lignocellulosic feedstock globally.
- Biosurfactant, dihydrolevoglucosenone, and ethyl acetate exhibited a GHG saving when shifting from fossil to bio-based feedstocks of 50%, 87%, and 56%, respectively.
- Monoethylene glycol (MEG) produced from sugar beet indicated a range of 57% to 83% in GHG emissions saving against coal and shale gas MEG as fossil-based counterfactuals, with higher emissions savings of up to 116% when lignocellulosic feedstock is used in its production.
- Holiferm UK LCA results demonstrated a 50% GHG saving potential for bio-based surfactants produced from rapeseed and corn starch.
- Methyl methacrylate (MMA) demonstrated GHG emissions savings ranging from 5% to 42% against MMA fossil-based counterfactual. This was lab-based experiments which has potential to scale up over time with an increased GHG emissions saving.
- It was not possible to find specific studies in our literature review that produced furandicarboxylic acid (FDCA) as a bio-based chemical in the UK. However, a non-UK study demonstrates a potential GHG saving for FDCA production of 28%. Nevertheless, non-UK study relating to starch from European wheat to make FDCA, which was then polymerised with plant-based MEG to make polyethylene furandicarboxylate (PEF) was reviewed with a fossil-based comparator being a PET bottle. The study results demonstrated a 62% GHG emissions saving against the counterfactual. Other literature reviewed suggest a potential GHG saving for bio-based PEF production of between 76% and 78%.

When compared with bioethanol as a road transport fuel these results reflect favourably. UK wheat grain derived ethanol for use as road transport fuel returns a GHG emission saving of 76-82% against fossil fuel average, this equates to 1.9-2.1 tonnes CO_2eq per tonne of ethanol.

Table 6. CO_2 savings of bio-based chemicals compared to fossil resource incumbent.

Chemical	GHG savings ($kgCO_2eq/kg$ of product)	GHG saving %	Notes
Lactic Acid (or as PLA)			
Lactic acid from MSW	2.44	55%	UK data used obtained from Fiberight. Fiberight utilises MSW as feedstock to produce bio-based LA assumed to displace synthetic LA.
Lactic acid from Wheat Grain	2.32	80%	Lactic acid as PLA produced from UK wheat grain assumed to displace fossil-based polyethylene, calculated from the North Energy Associates Ltd models.
Monoethylene glycol (direct sugar to MEG process)	2.15	116%	Bio-based MEG produced from forest residues as feedstock.
Ethyl Acetate (via ethanol)	2.5	50%	Bio-based Ethyl acetate produced using JM bio-based ethanol condensation technology
Ethylene (via ethanol)			
HDPE (Wheat straw)	5.41	243%	Wheat straw as the feedstock. Bio-based ethylene assumed to displace fossil-based Ethylene.
Wheat grain	2.91	65%	Ethylene produced from UK wheat grain assumed to displace fossil-based ethylene, calculated from the North Energy Associates Ltd models.
Sugar beet	3.24	72%	Ethylene produced from UK sugar beet assumed to displace fossil-based ethylene, calculated from the North Energy Associates Ltd models.
Lignocellulose (wheat straw)	4.23	94%	Ethylene produced from UK wheat straw assumed to displace fossil-based ethylene, calculated from the North Energy Associates Ltd models.
Methyl methacrylate	1.2	12%	Bio-based MMA. LCA non-UK data obtained from literature source.
Methanol (from CO_2)	2	95%	CO_2 from point source emissions feedstock and hydrogen from water hydrolysis using wind energy. We were not able to obtain UK data, hence this data is based on global data from the Methanol Institute.
Butanol (Acetone/Ethanol)			
Whiskey residues	3.18	69%	Bio-based butanol produced from UK whiskey residues as a feedstock. Assumed to displace fossil-based butanol. Functional unit used is per tonne of biomass feedstock.
Sugar beet	0.87	36%	Butanol produced from UK sugar beet assumed to displace fossil-based butanol, calculated from the North Energy Associates Ltd models with mass allocation.
Wheat grain	2.37	97%	Butanol produced from UK wheat grain assumed to displace fossil-based butanol, calculated from the North Energy Associates Ltd models with mass allocation.

Biosurfactant (rapeseed/corn starch	1.3	50%	Rapeseed/corn starch as a feedstock. Displaces fossil-based Naphtha
Furandicarboxylic acid	0.96	28%	Bio-based FDCA produced from wood chips as feedstock at a lab scale obtained from literature.
1,4-Butanediol			
Wheat grain	1.95	51%	1,4-Butanediol produced from UK wheat grain assumed to displace fossil-based 1,4-Butanediol, calculated from the North Energy Associates Ltd models
Sugar beet	1.01	27%	1,4-Butanediol produced from UK sugar beet assumed to displace fossil-based 1,4-Butanediol, calculated from the North Energy Associates Ltd models
Lignocellulose (Caedoon)	1.58	36%	Literature data for bio-based 1,4-Butanediol produced from lignocellulose (Caedoon) assumed to displace fossil-based 1,4-Butanediol
Succinic acid			
Wheat grain	2.24	45%	SA produced from UK wheat grain assumed to displace fossil-based Succinic acid, calculated from the North Energy Associates Ltd models.
Sugar beet	2.01	41%	SA produced from UK sugar beet assumed to displace fossil-based Succinic acid, calculated from the North Energy Associates Ltd models.
Lignocellulose (corn stover)	6.41	81%	Bio-based SA assumed to displace fossil-based SA. No wheat straw production of Bio-based SA was found in literature for the UK. The reference used assumed extraction of purified chemical from fermentation broth via liquid-liquid extraction method.
Dihydrolevoglucosenone	9.3	87%	Bio-based Dihydrolevoglucosenone from forestry residue as a feedstock. Not UK data, but product can potentially be produced in the UK using UK lignocellulosic feedstock.
Acetic acid (47% bio-based)	0.96	80%	Calculated based on displacement of natural gas used as feedstock with biomethane.

6. Economic impact of bio-based chemicals

This section presents findings from analysis of the economic potential of bio-based chemicals and materials based on i) recent economic performance of bio-based chemicals and materials companies and ii) UK trade data regarding the set of target chemicals and plastics identified as potential targets for future bio-based alternatives.

6.1 Approach

The economic analysis took a two-pronged approach. First, the study conducted a 'macro' economic analysis by collating company-level data for UK bio-based chemicals and materials companies using a combination of Standard Industrial Classification (SIC) codes[3], existing company lists[4] and experimental key terms-based identification of companies across several proprietary and open-source platforms including Bureau van Dijk and Beauhurst. Identification and refinement of the company dataset involved a 5-stage process, described in Annex 4.

Secondly, the study took a 'micro' or 'bottom-up' approach to produce estimates of the economic potential of specific 'target chemicals' identified as offering economic potential to the UK based on expert opinion and stakeholder contributions. It was originally envisaged that data pertaining to costs and revenues associated with bio-based chemicals and materials products could be collected directly from a number of the strategic companies involved in the stakeholder engagement component of the study. A detailed economic data collection template (Annex 4) was designed and circulated to company representatives that gave consent to be re-contacted following the initial stakeholder interview. A number of follow-up consultations were held and, while several companies were willing to contribute further economic data to the study, ultimately only three companies provided data at the level of granularity required to inform the bottom-up analysis.

Subsequently, in a further effort to capture data that could inform the bottom-up analysis the study team sought to gather relevant data from more than two dozen relevant research papers and credible sources of chemicals data[5]. While almost 100 unique datapoints were gathered against in-scope target chemical pathways, ultimately the coverage and consistency of the data did not allow for robust analysis of cost and benefits associated with individual target bio-based chemicals.

Therefore, following DESNZ recognition of the challenges associated with the "bottom-up" analysis, and in consultation with NNFCC, it was agreed that chemicals and plastics trade data would be used to provide some higher-level assessment of the economic potential of individual target chemicals.

It is important to note that the methods used to estimate bio-based chemicals and materials economic activity in this study are experimental. They do not use traditional Standard Industrial Classification (SIC) codes and are therefore not consistent with formal economic statistics produced by the Office for National Statistics, the Chemicals Industry Association, or other central government departments. Specifically, the analyses presented in this report use novel approaches to estimate the proportion of bio-based activity within shortlisted chemicals and materials companies using web-based employment data.

[3] SIC codes 201, 202 and 721.
[4] Including NNFCC's internal company lists.
[5] Including but not limited to https://www.chemanalyst.com/.

6.2 Key findings

The subsections below provide a synthesis of key findings contained in the full economic analysis paper (Annex 4).

6.2.1 Estimating bio-based chemicals and materials economic activity

A detailed process was undertaken to identify UK companies involved in producing bio-based chemicals and materials products. This included identification of 'dedicated' companies i.e., those for which bio-based activity is estimated to represent a high proportion of overall business activity and 'diversified' companies i.e., those for which bio-based activity represents a moderate or low proportion of overall business activity.

Dedicated bio-based chemicals and materials activity

The term 'dedicated' refers to those bio-based chemicals and materials companies for which production of bio-based products represents the majority of business activity. The bases for apportioning company activity are provided in detail in the main report and include a combination of Large Language Model (LLM) techniques and verification by industry experts.

A total of 117 'dedicated' bio-based chemicals and materials companies were identified[6]. In the last available year for which data is available (typically 2021 or 2022) these companies generated £1.1bn in UK revenues, employed approximately 2,300 people and contributed an estimated £340m in GVA.

Table 7. Economic Contribution of Dedicated Bio-based Chemicals and Materials Companies

Metric (UK, Latest Available Year)	Figure
Count of Companies	117
Turnover	£1.1bn
Employment	2,300
R&D Spend	£15m
GVA	£340m
Grants & Fundraising	£200m

Source: Bureau van Dijk, Perspective Economics

Diversified bio-based chemicals and materials activity

In addition, 'diversified' biochemicals and materials companies (i.e., those for which the production of bio-based products represents part of a broader portfolio) were estimated to generate £0.5bn in UK bio-based revenue, employ 900 people and contribute GVA of £100m (Table 8).

[6] In all but one instance, 100% of UK economic activity for companies identified as being 'dedicated' bio-based chemicals and materials companies was included in the aggregated totals. Based on consultation with the largest dedicated company – Croda – and given the significance of Croda's economic contribution, a lower proportion of 85% of UK economic activity was included within the aggregated total bio-based economic headlines.

Table 8. Economic Contribution of Diversified Bio-based Chemicals and Materials Companies

Metric (UK, Latest Available Year)	Figure
Count of Companies	451
Estimated Bio-based Turnover	£0.5bn
Estimated Bio-based Employment	900
Estimated Bio-based R&D Spend	£14m
Estimated Bio-based GVA	£100m

Source: Bureau van Dijk, Perspective Economics

Taking activity among dedicated and diversified companies together, bio-based chemicals and materials activity is estimated to generate more than £1.5bn in revenue, employ more than 3,000 people, and contribute more than £400m in GVA to the UK economy.

Table 9. Total Estimated Bio-based Chemicals and Materials Activity

Metric (UK, Latest Available Year)	Figure
Turnover	£1.6bn
Employment	3,200
R&D Spend	£29m
GVA	£440m

Source: Bureau van Dijk, Perspective Economics

Table 10 shows the top 10 dedicated and diversified bio-based chemical and materials companies included in the analysis by measure of UK employment.

Table 10. Dedicated and Diversified Company Examples

	Dedicated	Diversified
1	CRODA	JOHNSON MATTHEY
2	FUTAMURA	INEOS
3	ARGENT ENERGY[7]	SYNTHOMER
4	ENSUS	SYNGENTA
5	BIOCATALYSTS	ELEMENTIS
6	BIOLOGICAL PREPARATIONS	BPI
7	GREENERGY BIOFUELS	TENNANTS CONSOLIDATED
8	CORYTON ADVANCED FUELS	VICTREX
9	CELTIC RENEWABLES	WESTLAND HORTICULTURE
10	INGENZA	SCOTT BADER

Source: Bureau van Dijk

Growth and investment among dedicated bio-based chemicals and materials companies

Between 2019 and 2021/22, large and medium-sized dedicated bio-based chemicals and materials companies grew revenues by 15% and employment by 13%. Albeit from a lower base, growth among dedicated bio-based chemicals and materials companies between 2019 and 2021/22 was at least as strong as growth among similarly-sized diversified companies (i.e., those driven by non-bio-based activity). Large and medium-sized diversified companies increased revenues by 9% and

[7] Biofuel companies have been included because of their high potential to transition to bio-based chemical companies.

employment by 1% over the same period[8]. Dedicated bio-based chemicals companies driving economic growth include Biological Preparations Limited, Greenergy Biofuels and Ensus.

While double digit growth among dedicated bio-based chemicals and materials companies is encouraging, company data also shows that new dedicated company incorporations have flatlined compared to diversified companies since 2018. This suggests a need for policy supports that leverages growth among established high-potential bio-based chemical and materials companies, and also encourages new start-up and scale-up companies to enter the market.

Investment data shows that dedicated bio-based chemicals and materials companies have successfully secured grants and external fundraising to the value of almost £200m over the past decade[9]. Approximately three quarters of this total figure is private investment (£148m). While this total investment figure is insignificant compared to investment in other sectors (e.g., software), it does show that investment opportunities exist for innovative bio-based chemicals and materials companies. Table 11 shows the 10 dedicated bio-based chemicals companies that have received the most grants and investment since 2013. The most frequent investors in dedicated bio-based chemical and materials companies are Scottish Enterprise, Crowdcube and Sky Ocean Ventures (each involved in between 5 and 9 fundraisings). UK funds account for just under half of the total amount of fundraising involved in associated funding rounds (46%), US funds account for 30% and European funds account for 18%.

Table 11. Dedicated Grant and Investment Raising Companies

	Dedicated Bio-based Company Name
1	CELTIC RENEWABLES LIMITED
2	ALGAECYTES LIMITED
3	NOTPLA LIMITED
4	XAMPLA LTD
5	HOLIFERM LIMITED
6	EPOCH BIODESIGN LTD
7	CELLUCOMP LIMITED
8	INGENZA LIMITED
9	OCEANIUM LTD
10	BIO-SEP LIMITED

Source: Beauhurst

6.2.2 Trade in target chemicals and materials

As discussed at the outset of this section, the study was unable to obtain granular data that would enable like-for-like analysis of the costs and benefits associated with target bio-based chemical and materials production compared to fossil-based alternatives. In the absence of this data the study analysed import and export data as a proxy for understanding the potential significance of bio-based chemical alternatives to a selection of target fossil-based equivalents.

[8] Note caution due to difference in sample sizes. Dedicated company revenue growth (sample = 16), dedicated company employment growth (sample = 69); diversified company revenue growth (sample = 105), diversified company employment growth (sample = 107).
[9] Data via Beauhurst for dedicated companies since 2013.

Table 12 shows the fossil-based chemical codes selected as proxies for estimating the significance of each target chemical to the UK economy.

Table 12. Proxy Chemical Commodity Codes

	Scenario Chemical	Proxy Chemical Code(s)
1	Acetic acid	29152900 Salts of acetic acid (excl. inorganic or organic compounds of mercury) 29153100 Ethyl acetate
2	Ethylene	29012100 Ethylene
3	Lactic acid	29181100 Lactic acid, its salts and esters (excl. inorganic or organic compounds of mercury)
4	Ethyl acetate	29153100 Ethyl acetate
5	Methyl methacrylate	29161300 Methacrylic acid and its salts
6	Methanol	29051100 Methanol "methyl alcohol"
7	Butanol	29051300 Butan-1-ol "n-butyl alcohol"
8	Acetone	29141100 Acetone
9	Biosurfactants	34021300 Non-ionic organic surface-active agents, whether or not put up for retail sale (excl. soap)
10	Furandicarboxylic acid (FDCA)	29173600 Terephthalic acid and its salts
11	1,4-Butanediol	29053928 Butane-1,4-diol 29053926 Butane-1,4-diol or tetramethylene glycol
12	Succinic acid	29171920 Ethane-1,2-dicarboxylic acid or butanedioic acid "succinic acid" having a bio-based carbon content of 100% by mass
13	Dihydrolevoglucosenone	Not available

Each of these chemicals plays a different role in the UK economy – some are imported for direct use or as inputs into production of higher value products, others are produced in the UK and exported. Table 13 below provides a summary of the balance of trade (import minus export volumes) for each target chemical over the past decade. Eight of the target chemicals (highlighted) have been traded in significant volumes over time (c.10,000 tonnes or more). Three of these 'significant' chemicals are predominantly exported (Acetic acid, Ethylene, and Ethyl Acetate) and the remainder have been predominantly imported.

Table 13. Balance of Trade in Target Chemicals (10-year average, Tonnes)

	Target Chemical	Trade Balance	Balance of Trade
1	Acetic acid	-130,727	Export
2	Ethylene	-709,213	Export
3	Lactic acid	2,582	Import
4	Ethyl acetate	-128,326	Export
5	Methyl methacrylate	6,866	Import
6	Methanol	783,393	Import
7	Butanol	15,727	Import
8	Acetone	123,502	Import
9	Biosurfactants	60,600	Import
10	Furandicarboxylic acid (FDCA)	44,070	Import
11	1,4-Butanediol	753	Import
12	Succinic acid	-20	Export
13	Dihydrolevoglucosenone	-	-

Source: HMRC UK Trade Info

Table 14 shows the average volumes and values (exports) or cost (imports) for these higher-volume chemicals over the past decade, and the actual value / cost of UK exports and imports over the period (right-most column).

Table 14. Target Chemical Costs, Volumes and Value (10-year average / total, Tonnes)

Scenario Chemical	Trade Balance	Avg. Cost / Value Per Tonne	Volume (Tonnes, 10-Yr Ave)	Average Annual Cost / Value	10-Yr Value
Acetic acid	Export	£1,636	143,808	£106,844,472	£1,068,444,716
Ethylene	Export	£789	738,024	£549,782,422	£5,497,824,218
Ethyl acetate	Export	£685	138,007	£91,731,220	£917,312,195
Total Export Value					£7,483,581,129
Methanol	Import	£265	789,795	£205,651,715	£2,056,517,150
Butanol	Import	£846	15,963	£13,094,050	£130,940,500
Acetone	Import	£585	125,918	£72,422,904	£724,229,040
Biosurfactants	Import	£2,440	82,499	£199,902,573	£1,999,025,735
Furandicarboxylic acid (FDCA)	Import	£1,020	44,085	£40,656,057	£406,560,576
Total Import Cost					£5,317,273,001

Source: UK Trade Info

Trade data shows that over the past decade, UK companies have generated almost £7.5bn in revenue from the sale of fossil alternatives to target chemicals (acetic acid, ethylene and ethyl acetate) and have spent almost £5.5bn on imports of target chemical equivalents (methanol, butanol, acetone, biosurfactants and FDCA). It shows that the UK a) has the capacity and capability to generate substantive revenues from bio-based acetic acid, ethylene and ethyl acetate in future and b) has average annual demand of more than 50k tonnes of fossil equivalents to bio-based methanol, acetone and biosurfactants.

Extending this type of analysis to the target chemical production volumes provides an indication of the potential trade benefit of UK production[10]. As set out in Table 15 below, based on 2019 import costs and export prices, some of the highest value potential future UK opportunities are in the production of bio-based acetic acid (£270m), ethyl acetate (£191m) and methyl methacrylate (£186m)[11]. With the exception of acetic acid, all figures are assumed to be in addition to the value of fossil-based alternatives.

Table 15. Target Chemical Trade Value Opportunity (Gross)

	Trade Direction	2030 Scenario Production Volume (tonnes)	2040 Scenario Production Volume (tonnes)	2050 Scenario Production Volume (tonnes)	2030 Total Trade Benefit (£)	2040 Total Trade Benefit (£)	2050 Total Trade Benefit (£)
Lactic acid	Import	10,000	50,000	100000	£15,389,009	£76,945,043	£153,890,085
Monoethylene glycol	Import	-	50,000	200000	£ -	£26,745,403	£106,981,611
Ethyl acetate	Export	50,000	100,000	300000	£31,880,053	£63,760,106	£191,280,319
Ethylene	Export	50,000	200,000	200000	£38,310,744	£153,242,977	£153,242,977
Methyl methacrylate	Import	-	10,000	100000	£ -	£18,667,838	£186,678,380
Methanol	Import	-	10,000	100000	£ -	£2,425,093	£24,250,931
ABE	Import	10,000	50,000	50000	£6,717,928	£33,589,641	£33,589,641
Biosurfactant	Import	-	10,000	50000	£-	£25,303,527	£126,517,636
Furandicarboxylic acid	Import	-	10,000	50000	£-	£6,881,527	£34,407,636
1,4-Butanediol	Import	10,000	10,000	50000	£16,478,200	£16,478,200	£82,391,000
Succinic acid	Export	-	10,000	50000	£-	£14,065,000	£70,325,000
Dihydro-levoglucosenone	Export	10,000	50,000	200000	£7,160,000	£35,800,000	£143,200,000
Acetic acid (48% bio-based)	Export	50,000	200,000	580000	£23,319,426	£93,277,702	£270,505,336

Source: UK Trade Info, NNFCC, Perspective Economics

[10] Figures are taken from UK Trade Info and therefore reflect trade prices rather than specific chemical prices which tend to be lower.
[11] Trade direction is based on the balance of UK trade over the past 10 years. Where the UK has been a net importer of scenario chemical equivalents, future trade values reflect import cost savings, plus estimated export values (where not all UK production is required in the UK). Where the UK has been a net exporter of scenario chemical equivalents, future trade values reflect estimated production multiplied by current export prices per tonne (2019, unadjusted). N.B. figures have not been aggregated because the same fossil equivalent chemical is included in more than one scenario. Figures do not reflect any price differential for bio-based alternatives, including for example the likely higher value of FDCA compared to terephthalic acid. Changes to revenue derived from existing production e.g., ethanol and acetic acid are not considered in the report. Production estimates can only be realised if commercial appetite exists to produce bio-based alternatives.

7. Transition requirements

Based on stakeholder engagement and the outputs of the literature review, transition requirements are highlighted below:

Strategy: All stakeholders supported the need for a clearer vision for an industrial Net Zero Pathway that is aligned across government departments, including Defra, DSIT, DESNZ and DBT. The strategy needs to back the use of renewable carbon sources and commit investment into scaling technologies. Such a strategy should also lay out incentives for using renewable carbon, where the most benefit is to be had – both environmentally and economically.

Many stakeholders pointed to, how under the 'Inflation Reduction Act' in the USA, the administration has established new targets for the American bioeconomy, through its new 'Bold Goals for U.S. Biotechnology and Biomanufacturing' strategy, with ambitious goals for their chemicals and materials sector. Engineering biology and biomanufacturing are core to all this work. Theme 2 of the strategy seeks alternative processes to produce chemicals and materials from renewable biomass and intermediate feedstocks by developing low-carbon-intensity product pathways and promoting a circular economy for materials. Achieving these goals will position the United States at the forefront of a vibrant global bioeconomy while producing net-zero or net-negative emissions, reducing use of and reliance on fossil fuels, and increasing use of recyclable-by-design chemicals and materials like bio-based products. Alongside this, they have set ambitious targets (Figure 4).

Theme 2: Chemicals and Materials

Goal 2.1: Develop Low-Carbon-Intensity Chemicals and Materials – In 5 years, produce >20 commercially viable bioproducts with >70% reduced lifecycle GHG emissions over current production practices.

Goal 2.2: Spur a Circular Economy for Materials – In 20 years, demonstrate and deploy cost-effective and sustainable routes to convert bio-based feedstocks into recyclable-by-design polymers that can displace >90% of today's plastics and other commercial polymers at scale.

Figure 4. US Inflation Reduction Act, Theme 2 goals

Whilst the US's aspirational targets may seem difficult to achieve, the administration has put financial resources behind the policy to stimulate production of bio-based chemicals.

Policy and Regulation: Stakeholders felt the government had a crucial role to play in promoting the adoption of bio-based chemicals through supportive policies and regulations. This includes providing incentives such as tax credits, grants, and subsidies for research and development, production, and use of bio-based chemicals.

- For example, in January 2017 France mandated use of compostable materials for single-use supermarket bags and food packaging, leading to growth in its bio-based materials industry. Stakeholders felt the UK should investigate and implement similar policies designed to promote the bio-based chemicals listed in this report.
- Another example cited by many stakeholders was the policy around recycled plastics and tax incentives if plastics contain more than 30% recycled plastic by content. It was strongly felt that this should be rolled out to all materials containing more than 30% biomass, which would aid the transition to bio-based materials via the mass balance approach.
- Regulatory incentives would create market pull for bio-based chemicals and drop in equivalents. This, for example, has been successful in fuels (RTFO) and Sustainable Aviation Fuels.

- Stakeholders felt that lessons could be learnt from the US, where they have a bio-preferred scheme[12], that aims to assist in the development and expansion of markets for bio-based products. The program was created by the 2002 Farm Bill (legislation) and expanded as part of the 2014 Farm Bill. For example, UK government could specify that the NHS must procure certain bio-based materials (e.g., disposable gloves) by a certain time. This would drive market demand.
- In addition, stakeholders thought that the UK could mimic elements of the US Inflation Reduction Act[13].
- Stakeholders noted the need to be able to match and offer greater incentives provided by other countries if some other natural barriers (e.g., feedstock availability) are to be overcome.
- Stakeholders agreed that for biomass to be given an equal playing field to fossil carbon, that subsidies for oil and gas need to be stopped, or reduced, and/or subsidies for biomass feedstocks should be implemented.
- The need for standardised carbon accounting was agreed by the majority of stakeholders, alongside a tax on fossil-based carbon extraction and emissions. It is suggested that such carbon taxes need to be applied from beginning of the supply chain, and at point of emissions, and that they should start off low, and then increase.
- All stakeholders noted the need to simplify REACH registration for chemicals made from bio-based feedstocks, and to subsidise the cost. Stakeholders noted also that the process for getting permits for use of waste streams needs to be simplified to enable biomass to be used at scale for bio-based chemicals. Stakeholders also felt green trade deals would benefit the bio-based industry.

Access to Feedstocks: Stakeholders raised the need of increasing availability of bio-based feedstocks at scale and at a competitive price. The importance of creating appropriate systems for biowaste collection and valorisation was also highlighted. Concerns raised over feedstock availability included:

- There may not be enough biomass for all potential applications.
- Competition for biomass feedstock from other users, e.g., SAF.
- Ideally, biomass should be available close to the existing processing assets – what is available may be in the wrong place.

Funding and Investment: Consistent long-term funding for research and development in bio-based chemicals, including funding for academic institutions, research organizations, and private companies is required. This financial support would help accelerate technological advancements, scale-up production, and reduce costs, making bio-based chemicals more competitive with their conventional counterparts.

- Research funding focussed on developing cost-effective ways to produce bio-based chemicals and their derivativities, and on ways to scale them up to commercial products, will underpin viable commercial models.
- Stakeholders also noted that UK companies need technology testing and scale up services, and open access piloting and demonstration facilities. Technology advances in feedstock pretreatment and the supply of low-cost renewable sugars will also be an important enabler for the development of bio-based chemicals.
- The Horizon Europe programme and the Circular Bio-based Europe Joint Undertaking (CBE JU) programme was mentioned by several stakeholders as an example the UK could

[12] FACT SHEET: Overview of USDA's BioPreferred Program | USDA
[13] Inflation Reduction Act Guidebook | Clean Energy | The White House

replicate. CBE JU is a €2bn partnership between the European Union and the Bio-based Industries Consortium (BIC) that funds projects advancing competitive circular bio-based industries in Europe. It funds projects across the full TRL scale.

Infrastructure Development: Stakeholders highlighted the need for investment into the development of infrastructure to support the production, storage, and distribution of bio-based chemicals. This includes building or retrofitting facilities for bio-based chemical manufacturing, establishing storage and transportation networks, and promoting the development of sustainable feedstock supply chains. Help is required to finance infrastructure for demo plants and finance for equipment. The (affordable) availability of pilot-scale facilities to de-risk scale-up and commercialisation, was noted by all stakeholders, to enable innovation activities to remain in the UK.

Market Demand and Awareness: Stakeholders felt the Government could help create market demand for bio-based chemicals by raising awareness among consumers, industries, and procurement agencies about the benefits of these products. Promoting labelling and certification schemes, consumer education campaigns, and sustainable public procurement policies could stimulate demand and encourage industries to transition to bio-based chemicals. Communication and the language used to describe bio-based products also needs to be assessed and simplified to ensure consumers are not led astray over product claims.

Collaboration and Partnerships: Stakeholders believe the Government can foster collaboration between academia, industry, and other stakeholders to drive innovation and knowledge sharing in the bio-based chemicals sector. Public-private partnerships, technology transfer programs, and collaborative research initiatives could accelerate the development and adoption of bio-based chemicals. A few stakeholders noted the success of the Vaccines Taskforce during the pandemic and thought the Government should create a Climate Task Force to drive forward the UK's response to global warming.

International Cooperation: Since climate change is a global issue, stakeholders felt that the Government should be collaborating on an international level on joined up research projects, harmonising standards, sharing best practices, and facilitating trade in bio-based chemicals. This would help create a level playing field, promote market access, and encourage global adoption of bio-based chemicals.

Sustainability and Life Cycle Assessments: All stakeholders noted that the Government should consider the environmental and social sustainability of bio-based chemicals throughout their life cycle. Robust sustainability standards and life cycle assessments are needed to ensure that bio-based chemicals deliver significant environmental benefits compared to conventional fossil-based alternatives. Considering the impact of embedded carbon in chemicals and end of life release is critical in ensuring circularity through biomass use. The understanding and acceptance of mass balance as a mechanism to enable transition from fossil based to bio-based at scale, was also noted. For LCAs stakeholders agree that wider impacts beyond climate change are important to consider, such as resource depletion, acidification, eutrophication, eco- and human toxicity.

Key enablers for a transition to biomass as a feedstock for bio-based chemicals: Stakeholders were asked what key enablers were required to accelerate a transition to bio-based chemical production, to make products that were commercially and technologically viable, which included:

- Provision of cost effective renewable low-carbon energy, through a greener, renewable grid
- Advanced Machine Learning and AI tools to increase efficiency and reduce lead times
- Production of domestic low-cost cellulosic sugars
- Improvements in 1st & 2nd gen sugars from biomass – especially managing the transition
- Faster, cheaper, scalable biotech. Including:
    - Easier retrofit
    - Scalable and versatile biotransformations

    - Better engineering of bioprocesses
    - Improved extraction and dewatering processes
    - Technology that can be used for distributed production and supply
    - Better deoxygenation technologies and economic uses for released O_2.
- A UK waste regime, emissions trading schemes and energy policy, that support using waste or biomass for chemicals
- Shift the tax burden between sourcing and emissions to level the playing field and distribute the costs across the supply chain and consumer.

8. Conclusions and further actions

Based on all study findings, we highlight below the main conclusions and areas for further action, which are all synthesised in Figure 5.

8.1 Conclusions

By 2050, the UK bio-based chemicals industry has the potential to significantly grow, producing over 2 million tonnes of bio-based chemicals, contributing to 5.2 million tonnes CO_2eq GHG savings and £1.6bn in value to the UK economy.

8.1.1 UK potential to produce bio-based chemicals

Although the future availability of UK domestic biomass is uncertain, analysis shows the potential to produce over two million tonnes of the target chemicals.

All selected chemicals are produced from the sugar fraction of biomass feedstock, therefore with the appropriate development of co-product streams (e.g., protein from grains, and hemicellulose and lignin from lignocellulosic biomass), the actual output of all chemicals would be considerably higher than two million tonnes.

8.1.2 Carbon savings

This review demonstrates that the bio-based chemical industry has a significant potential to produce chemicals and materials with a reduced climate change impact; compared to functionally equivalent fossil products.

Where possible GHG emission savings have been drawn from LCA studies based on UK production and therefore using UK process emission data. Where this has not been possible an attempt has been made to use UK relevant information.

The GHG saving potential for individual chemicals ranges from 1-9tonnes of CO_2eq per tonne of bio-based chemical, with an average saving of 2.5tonnes CO_2eq per tonne.

With respect to bioenergy comparisons these results reflect favourably when compared to UK wheat grain derived ethanol for use as road transport fuel. UK bioethanol returns a GHG emission saving of 76-82% against the fossil fuel average which equates to 1.9-2.1tonnes CO_2eq per tonne of ethanol.

Based on the production scenarios explored in the study there exists the potential to save 0.48 million, 2.0 million and 5.2 million tonnes of CO_2eq emissions in 2030, 2040 and 2050 respectively.

However it should be recognised that a review of this nature, where LCA results are compared across studies and counterfactual fossil based chemical emissions values are derived separately to the bio-based chemical, has significant limitations and results carry considerable uncertainty. Therefore the specific GHG emissions saving values should be treated with caution. Key areas of uncertainty are the accuracy and alignment of the LCA approaches used to determine fossil fuel counterfactuals, the alignment of LCA methods used across the bio-based chemical studies in respect to allocation methods, the treatment of biogenic carbon across the bio-based chemical studies and transferability of LCA results for studies performed outside of the UK.

8.1.3 Economic impact

Given appropriate support and subject to feedstock availability, the chemical sector has the scale, capacity and transferrable skills necessary to make the UK a leading location for the production of bio-based chemicals and materials on the basis that:

- The UK chemical sector contributes almost £31bn in GVA to the UK economy and accounts for almost one fifth of total UK business R&D expenditure in 2023. Global multinational chemicals companies including Sabic, ExxonMobil, Huntsman, Essar Oil and AkzoNobel see considerable opportunity in UK chemicals and materials operations.
- In 2022 companies within the serviceable addressable market for bio-based chemicals and materials employ around 130,000 people, generate £60bn in turnover and invested c.£680m in R&D.
- The UK already has a core of bio-based chemicals and materials activity on which to build. 117 dedicated bio-based chemicals and materials companies identified through this study already generate more than £1bn in turnover and increased their employment base by almost 20% between 2018 and 2022.

Growing bio-based chemicals and plastics activity in the UK will require further deep and meaningful engagement with strategically significant companies across the serviceable addressable market.

Engagement should focus on:

- Expanding existing bio-based activity among larger dedicated bio-based chemicals companies such as Croda, Futamura, Argent Energy and Ensus.
- Supporting high-growth companies such as Celtic Renewables and Holiferm to continue improving processes, reducing costs and accessing new markets.
- Engaging with larger diversified bio-based chemicals and materials companies such as Johnson Matthey, Syngenta and Ineos to convert more of their UK activity to bio-based.
- Reigniting the start-up bio-based chemicals and plastics ecosystem, ideally with 'buy-in' from existing bio-based market incumbents and / or larger diversified companies.

From a trade balance perspective, UK companies have generated more in target chemicals exports than they have spent on imports over the past decade, driven by export of cracker products (ethylene and propylene).

Removing cracker products from the target chemicals group flips the average balance of trade over time by more than £0.5bn, from positive c.£300m to negative c.£300m, highlighting the historic significance of cracker products to the UK economy.

Looking specifically at target chemicals, estimates produced using scenario production values and trade data suggests that future potential opportunities may be highest in the production of bio-based acetic acid, ethyl acetate, and methyl methacrylate.

Table 16. The economic and environmental potential of bio-based chemicals to the UK by 2050

As of today, the global chemicals industry relies on fossil resources for 88% of its feedstock and contributes to ~10% of global annual greenhouse gases. The bio-based chemicals industry currently generates an estimated £1.6bn in revenue.

Intervention	By 2040			By 2050		
Manufacturing capability: Distributed	Distributed manufacturing capacity of 180,000 tonnes			Distributed manufacturing capacity of 500,000 tonnes		
Manufacturing capability: Biorefinery	6 biorefineries type facilities with a capacity of 420,000 tonnes			6 biorefineries type facilities with a capacity of 1,000,000 tonnes		
Manufacturing capability: Business as usual	200,000 tonnes of bio-attributed chemical capacity			580,000 tonnes of bio-attributed chemical capacity		
Transformations required	UK government to develop a unified cross-departmental biomass utilisation hierarchy and associated joined up policies and regulatory environment that ensures sustainably sourced biomass and biowastes are prioritised for highest value materials and products, to derive the maximum value from our bio-resources					
Key enablers	Increase availability of sustainable biomass, low cost accessible renewable energy; access to green hydrogen; transparent data sharing					
Bio-based chemical	**Volume produced (tonnes)**	**CO_2e savings**	**Economic value £**	**Volume produced (tonnes)**	**CO_2e savings (tonnes CO_2eq/tonne)**	**Economic value £**
Lactic acid	50,000	122,00	76,945,000	100,000	244,000	153,890,000
Monoethylene glycol	50,000	108,000	26,745,000	200,000	430,000	106,982,000
Ethyl acetate	100,000	250,000	63,760,000	300,000	750,000	191,280,000
Ethylene	200,000	582,000	153,243,000	200,000	582,000	153,243,000
Methyl methacrylate	10,000	12,000	18,668,000	100,000	120,000	186,678,000
Methanol	10,000	20,000	2,425,000	100,000	200,000	24,251,000
Dihydrolevoglucosenone	50,000	465,000	35,800,000	200,000	1,860,000	143,200,000
Succinic acid	10,000	20,000	14,065,000	50,000	101,000	70,325,000
Butanediol	10,000	10,100	16,478,000	50,000	51,000	82,391,000
Butanol, acetone and ethanol	50,000	159,000	33,590,000	50,000	159,000	27,208,000
Biosurfactant	50,000	65,000	25,304,000	100,000	130,000	126,518,000
Furandicarboxylic acid	10,000	9,600	6,882,527	50,000	48,000	34,408,000
Acetic acid	200,000	192,000	93,277,702	580,000	556,800	270,505,000
	By 2040			**By 2050**		
TOTAL IMPACT	**800,000 tonnes bio-based chemicals**	**2,305,000 tonnes CO_2e savings**	**560,700,000 economic value £**	**2,080,000 tonnes bio-based chemicals**	**5,231,000 tonnes CO_2e savings**	**1,570,878,000 economic value £**

By 2050, the UK bio-based chemicals industry has the potential to significantly grow, producing over 2 million tonnes of bio-based chemicals, contributing to 5.2million tonnes CO2eq. GHG savings and £1.6bn in value to the UK economy.

8.2 Requirements and next steps

In order to promote the development of a bio-based chemical industry in the UK, government support should be utilized in order to encourage the advancement of novel manufacturing processes and the production of new bio-based drop-in chemicals and new-to-market products.

However, it is clear that further development is needed in this area to develop effective policies that will help to drive the bio-based chemical industry and the wider bio-based economy going forward.

Requirements and next steps		
Overarching action	1	UK government to develop a unified cross-departmental biomass utilisation hierarchy and associated joined up policies and regulatory environment that ensures sustainable sourced biomass and biowastes are prioritised for high value materials and products, to derive the maximum value from our bio-resources.
Accelerating the transition to bio-based chemicals	2	Recognition of the benefits of the bioeconomy, and bio-based chemicals, with a dedicated long-term strategy.
	3	Investment frameworks for biomanufacturing of bio-based chemicals, including access to risk capital, enabling multi-scale biorefining facilities.
	4	Innovation principle-applied R&D priorities for bio-based chemicals, digital and AI advancement, intellectual property and innovation protection, plus skills development to support the transition away from fossil resources.
	5	Ensure sustainable government procurement, by implementing a bio-preferred procurement scheme, where the use of bio-based feedstocks is incentivised over fossil-based incumbents.
	6	Remove the Plastic Packaging Tax from certified bio-based packaging materials containing more than 30% bio-based content.
	7	Develop and publish a standardised LCA methodology that considers all the necessary parameters to put bio-based chemicals on a level playing field with their fossil incumbents.
	8	The mass balance approach for bioderived materials should be promoted
	9	Endorse trustworthy certification systems and standards for the sustainable sourcing of biomass feedstocks - clear sustainability criteria and incentives for labels.

Figure 5. Actions to support bio-based chemical industry development

ANNEX 1

Background and Context

The Bioeconomy Consultants

NNFCC

Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

Literature Review

Prepared for Department of Energy Security and Net Zero

This report should be read in conjunction with associated reports as part of project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

June 2023

Release Date: *June 2023*

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Disclaimer

While NNFCC considers that the information and opinions given in this work are sound, all parties must rely on their own skill and judgement when making use of it. NNFCC will not assume any liability to anyone for any loss or damage arising out of the provision of this report.

NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products.

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Definitions

1,3 - BDO	1,3-butanediol
BBIA	Bio-based and Biodegradable Industries Association
BEIS	Department for Business, Energy & Industrial Strategy
C&I	Commercial & industrial
CCUS	Carbon capture utilisation & storage
CEN	The European Committee for Standardization
CIA	Chemical Industries Association
CO_2	Carbon dioxide
DESNZ	Department for Energy Security & Net Zero
EV	Electric vehicle
FCC	Fluid catalytic cracker
FDCA	2,5-furandicarboxylic acid
GDP	Gross domestic product
GHG	Greenhouse gas
ha	Hectare
HDPE	High density polyethylene
HGV	Heavy goods vehicle
HMF	Hydroxymethylfurfural
IB	Industrial biotechnology
JRC	Joint Research Council
LCA	Life cycle assessment
LDPE	Low density polyethylene
MEG	Monoethylene glycol
MSW	Municipal solid waste
NIBB	Networks in Industrial Biotechnology and Bioenergy
OSR	Oilseed rape
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PLA	Polylactic acid
PVC	Polyvinyl chloride
REACH	Registration, evaluation, authorisation and restriction of chemicals
UKRI	UK Research & Innovation
wt%	Weight percent

Executive Summary

The global chemical industry currently generates around $4.7 trillion in annual revenue, representing approximately 4% of global GDP, and it is expected to grow considerably in the coming years as developing economies continue to advance and society places greater demand on the production of affordable functional materials and products to improve the quality of lives around the world.

According to BP's "Energy Outlook 2023", global oil demand will plateau over the next 10 years or so, before experiencing a steady decline throughout the 2030s and beyond. The single biggest factor driving this decline in oil consumption is believed to be linked to the reduction of gasoline and diesel fuel use in road transport. With gasoline and diesel consumption waning, oil refineries must therefore look to adapt their petrochemical outputs in order to remain economically feasible in the future. Whilst the use of oil in transport is steadily on the decline, the use of oil in petrochemical production still has sufficient room to grow. Thus, crude-to-chemicals is rapidly becoming the largest driver of worldwide oil demand, and as such, petrochemical applications will soon dominate the global oil industry.

Petrochemicals currently account for around 12% of global oil demand. Not only are fossil fuels used as the primary feedstocks for the production of petrochemicals, but they are also used to generate the energy, heat and pressure required during the manufacturing processes employed. As a result, industrial chemistry's use of petroleum and natural gas accounts for approximately 14% of all greenhouse gases (GHGs) emitted globally.[14] Therefore, as part of a wider move towards a global economy based on renewable energy, a reduced dependence on finite fossil fuels, and less GHGs emitted to the atmosphere, it is a key aim of the chemical industry to minimise process emissions and to improve the overall sustainability of the sector. In order to boost the sustainability of chemicals manufacturing, there are a number of changes that can be made to both the products and processes that traditionally depend upon the use of oil and gas. The first of which would be to employ renewable energy in place of fossil-derived fuels during chemical manufacturing processes. The second of which would be to de-fossilise chemical feedstocks using renewable biomass as an alternative source of carbon.

In the UK, the chemical industry is the country's second largest manufacturing sector (behind machinery and transport equipment) accounting for over £54bn in exports and £30.7bn in value added to the UK economy in 2021. The most prominent challenge currently facing the UK's chemical sector lies in the current cost of crude oil and natural gas, ultimately caused by Russia's invasion of Ukraine. In looking to mitigate the impacts caused by high energy and feedstock prices, it is important for the UK's chemical sector to adapt in order to move forward. One way of avoiding these impacts, is through the use of renewable energy in place of fossil fuels, and the use of renewable biomass as carbon feedstocks. If the UK chemical industry was to transition to the more widespread use of biogenic feedstocks over the use of oil and gas, it is imperative to ensure that sizable amount of biomass can be supplied domestically in order to avoid the need to import. Key biogenic feedstocks available in the UK include: cereal crops (e.g., wheat, barley, oats, oil seed rape) & cereal crop residues; sugar beet & sugar beet pulp; forestry biomass & forestry residues, perennial ryegrass, an industrial residues. However, in order for a chemical

14) Can the world make the chemicals it needs without oil?, https://www.science.org/content/article/can-world-make-chemicals-it-needs-without-oil [accessed June 2023].

industry to be sustained on the use of biomass feedstocks, current volumes available must be increased through sufficient policy incentives and favourable subsidies for feedstock producers.

1 Global Petrochemical Production

Petrochemicals are a class of chemicals derived from petroleum (i.e., crude oil) and natural gas, they are used to manufacture a diverse catalogue of downstream industrial and consumer products (Figure 6). It is estimated that roughly 96% of all globally manufactured goods are produced using petrochemicals as feedstocks. From packaging materials to textiles, to construction supplies and automotive products, petrochemicals play an essential role in market applications across the entire global economy.[15]

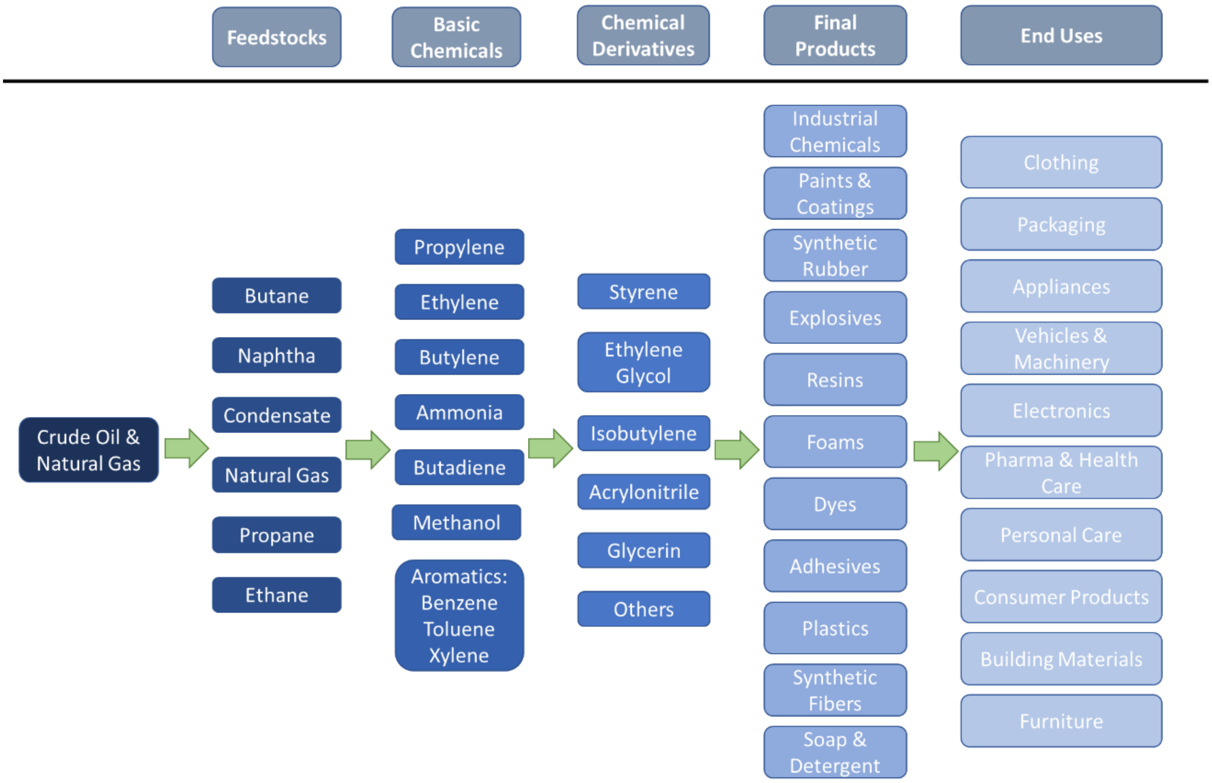


Figure 6: Petrochemical product flow from raw materials (crude oil and natural gas) to feedstocks, basic chemicals, chemical derivatives, final products, and end uses in industrial and consumer applications.[16]

Crude oil and natural gas are complex chemical mixtures that are generally unsuitable for direct use. Therefore, oil refining and gas processing are employed to convert mixtures into a range of fuels and petrochemical feedstocks. Petrochemicals can then be processed further to yield a selection of "base chemicals" such as ethylene, propylene, butylene, ammonia, butadiene, methanol, benzene, toluene and xylene. These base chemicals are recognized as being fundamental building blocks in the production of more complex chemical derivatives, polymers and materials.[17] Figure 7 highlights the most prominent base chemicals manufactured globally, and the approximate proportions in which they are consumed.

15) Systemiq, Planet Positive Chemicals, https://www.systemiq.earth/wp-content/uploads/2022/10/Main-report-v1.22.pdf [accessed June 2023].
16) CER, Market Snapshot: Petrochemical products in everyday life, https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2018/market-snapshot-petrochemical-products-in-everyday-life.html [accessed June 2023].
17) AFPM, How Petrochemicals are produced, https://www.afpm.org/industries/operations/how-petrochemical-produced [accessed June 2023].

It demonstrates that ethylene, propylene and methanol are the most widely manufactured and globally consumed base chemicals.

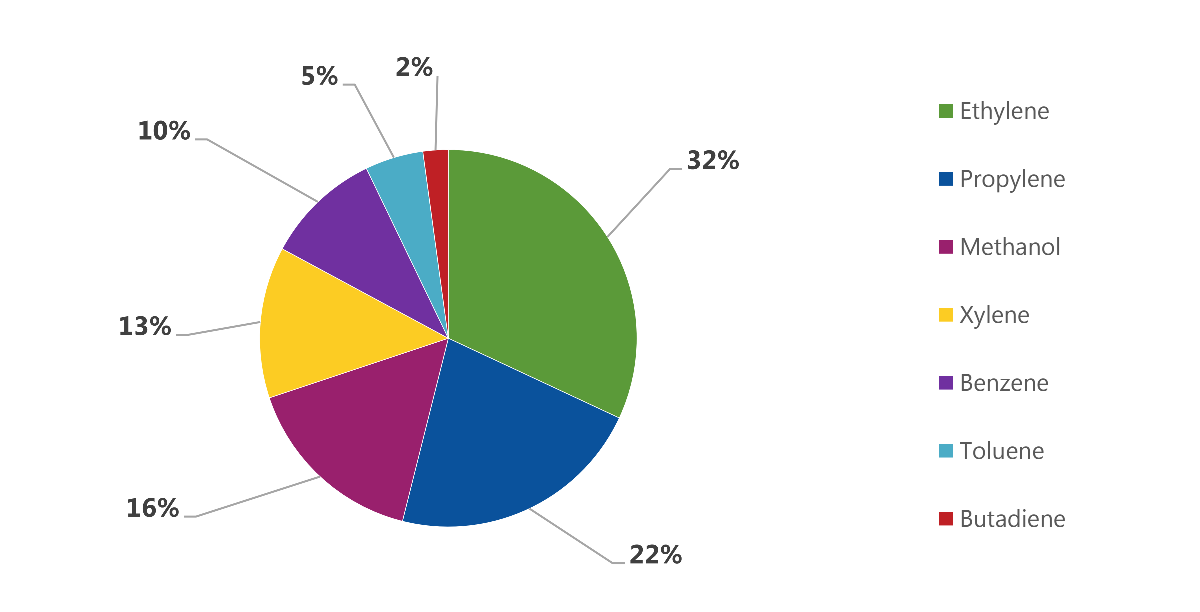


Figure 7: Distribution of primary petrochemical consumption worldwide in 2022, by type.[18]

Throughout the 20th century and up until today, the petrochemical industry has grown to become one of the world's largest and most important industries. It is understood that at present, petrochemicals account for roughly 12% of global oil demand, a share that is anticipated to increase in the coming decades as the demand for chemicals (for the production of plastics, fertilisers, and other consumer products) grows rapidly around the world.[19]

It is estimated that the global chemical industry currently generates around $4.7 trillion in annual revenue, representing approximately 4% of global GDP, and it is responsible for the employment of over 15 million people worldwide.[20] China (€1.7 trillion in annual chemical sales), followed by the EU27(€590bn in annual chemical sales) and the US (€430bn in annual chemical sales), account for the majority of global chemicals production, with China alone accounting for over 40% of chemical sales in 2021.[21]

The global chemical market is expected to grow considerably in the coming years as developing economies continue to grow and society places greater demand on the production of affordable functional materials and products to improve the quality of lives around the world. Take, for example, plastics. Worldwide plastic demand in recent years has outpaced that of all other bulk materials (such as steel, aluminium, and cement) having nearly doubled since the year 2000. It is understood that

18) S&P Global, Petrochemical Industry Overview, https://www.spglobal.com/commodityinsights/en/ci/products/petrochemical-industry-chemical-economics-handbook.html, [accessed June 2023].
19) IEA, The Future of Petrochemicals, https://www.iea.org/reports/the-future-of-petrochemicals [accessed June 2023].
20) Systemiq, Planet Positive Chemicals, https://www.systemiq.earth/wp-content/uploads/2022/10/Main-report-v1.22.pdf [accessed June 2023].
21) CEFIC, https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/profile/#h-europe-is-the-second-largest-chemicals-producer-in-the-world [accessed June 2023].

advanced economies (e.g., the US and the EU) currently use up to 20 times as much plastic compared with developing economies on a per capita basis. This highlights the potential for market growth, should developing nations look to consume plastics at a similar level as advanced nations. Although substantial increases in recycling are expected, as well as efforts to curb the use of single-use plastics (especially in areas like Europe, Japan and Korea), it is believed that these endeavours will be far outweighed by the increase in plastic utilisation (and disposal) across emerging economies.[22]

Plastics represent just one group of products derived from petrochemical feedstocks. Others include fertilisers, personal care products, pharmaceuticals, paints, coatings, dyes and fibres – all markets which are set to expand as emerging economies develop. A growth in demand for petrochemical products will mean that petrochemicals are set to account for over a third of the growth in oil demand by 2030, increasing to almost a half by 2050. Furthermore, the petrochemical sector is also expected to utilise an additional 56bn m^3 of natural gas by 2030, the equivalent of roughly half of Canada's total gas consumption today.[23]

2 Oil Refineries – The Transition from Fuel to Chemicals

Oil refineries operate by converting crude oil into petroleum products for use as fuels in transport, heating, and electricity generation; for the paving of roads (i.e., asphalt); and as feedstocks for the production of chemicals. It is estimated at present, that most refineries around the world convert between 5-20% of incoming crude oil into petrochemical feedstocks, whilst the remainder is primarily directed towards the generation of fuels (e.g., gasoline, distillate fuel oil (i.e., diesel), kerosene for use in jet fuels, petroleum coke to feed coal-fired power stations, and heavy fuel oil for use in industrial boilers and ocean-going ships).[24]

Gasoline accounts for the largest share of total petroleum products followed by diesel, and together these outputs amount to roughly two thirds of the overall products originating from a typical oil refinery (Figure 8).[25] The primary use of both gasoline and diesel fuels is in transport (e.g., cars, HGVs, light trucks, motorcycles, and buses), and according to BP's "Statistical Review of World Energy 2022", roughly 1.8 million b/d of gasoline and 1.3 million b/d of diesel/gasoil was consumed globally throughout 2021.[26]

22) IEA, The Future of Petrochemicals, https://www.iea.org/reports/the-future-of-petrochemicals [accessed June 2023].
23) IEA, The Future of Petrochemicals, https://www.iea.org/reports/the-future-of-petrochemicals [accessed June 2023].
24) C&EN, Why the future of oil is in chemicals, not fuels, https://cen.acs.org/business/petrochemicals/future-oil-chemicals-fuels/97/i8 [accessed June 2023].
25) EIA, Oil and petroleum products explained, https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-inputs-and-outputs.php, [accessed June 2023].
26) BP, Statistical Review 2022, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf [accessed June 2023].

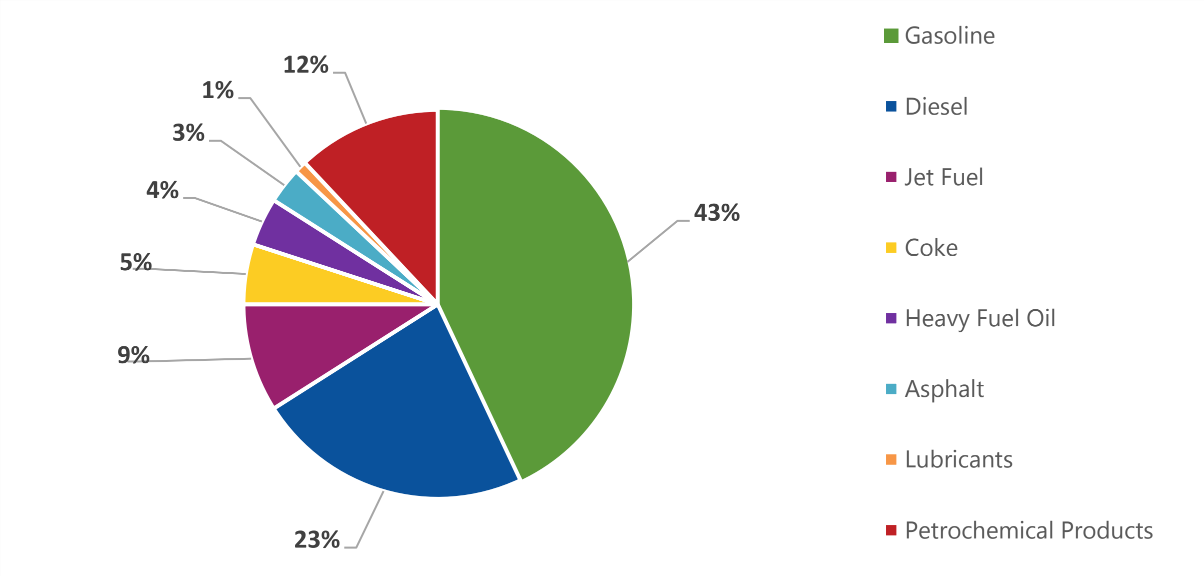


Figure 8: Typical share of petroleum products originating from an oil refinery.[27]

The role of oil in transport is rapidly declining however, as vehicles are becoming more fuel efficient and are increasingly fuelled by alternative energy sources. According to BP's "Energy Outlook 2023", global oil demand will plateau over the next 10 years or so, before experiencing a steady decline throughout the 2030s and beyond. The single biggest factor driving this decline in oil consumption is believed to be linked to the reduction of gasoline and diesel fuel use in road transport.[28] Furthermore, a decrease in oil consumption is to be expected across all other modes of transport, reflecting a general shift towards lower-carbon energy sources. This shift will be dominated by the electrification of cars and light-duty vehicles, and the use of bio- and hydrogen-derived fuels in heavy goods vehicles, buses, planes and ships for example. In road transport, the number of electric (including plug-in hybrid) cars and light-duty vehicles has the potential to increase from around 20 million in 2021, to between 550-700 million in 2035, and 2bn by 2050 (under an accelerated and net-zero scenario). Electric passenger cars will account for the majority of new car sales by the mid-2030s, supported by a combination of tighter regulations on the emissions of vehicles, substantial improvements in the costs of electric vehicles (EVs), growing choice amongst EV options on the market, and a growth in EV preference and acceptability amongst consumers.

With gasoline and diesel consumption waning, oil refineries must therefore look to adapt their petrochemical outputs in order to remain economically feasible. Whilst the use of oil in transport is steadily on the decline, the use of oil in petrochemical production still has sufficient room to grow. Thus, crude-to-chemicals is rapidly becoming the largest driver of worldwide oil demand, and as such, petrochemical applications will soon dominate the global oil industry.

Oil companies and engineering firms already recognise this and have begun installing new equipment and designing new processes in order to seize upon these trends. A typical oil refinery uses fractional

27) Petronaft, What are the main petroleum products in the world? https://www.petronaftco.com/main-petroleum-products/ [accessed June 2023].
28) BP, Energy Outlook, https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html [accessed June 2023].

distillation to separate crude oil into its constituent parts (e.g., gasoline, naphtha, propane, heavy diesel oil and vacuum gas oil etc.) followed by the use of a hydrocracker or a fluid catalytic cracker (FCC) to break down longer chained molecules into shorter ones. Hydrocracking is ideal for the production of diesel, naphtha and kerosene for jet fuel, with any naphtha generated sent to a steam cracker to produce olefins, or to a reformer to produce aromatics. Given recent trends in the demand for petrochemicals, refineries are now being reconfigured to generate more chemical outputs – with more hydrocrackers now targeting naphtha rather than diesel production, to subsequently manufacture more olefins and aromatics. Alternatively, FCC units can be used to break down vacuum gas oil into gasoline, whilst at the same time generating olefins such as propylene (making up roughly 5-20% of the process outputs). Again, due to recent trends in the demand for petrochemicals, many refiners are now running their FCCs at high temperatures for long residence times in order to increase propylene yields to well over 20%.[29]

In the past, the relationship between oil refining and the production of petrochemicals was traditionally a separate one. Refineries typically focused on the production of fuels, while components like naphtha would be sold to operators of steam crackers in order to produce ethylene, propylene, and other basic chemical building blocks independently. Although many integrated oil/petrochemical refineries currently exist, their aim traditionally is not to maximise the production of petrochemicals, rather to benefit from the synergies between a refinery and a petrochemical production site (i.e., shared utilities and the ability to feed naphtha directly into an adjacent steam cracker). However, whenever a new-build refinery is considered today, a major goal of the project is to integrate petrochemical production and to maximise chemical outputs beyond what has been previously seen.[30]

A notable example of a modern-day crude-to-chemicals refinery can be seen in the Zhejiang Petrochemical complex based in Zhoushan, China. This new site is capable of processing up to 800,000 barrels of crude oil per day, and it is estimated that as much as 50% of the refinery's outputs (roughly 20 million tonnes per annum) will be petrochemical products. Xylenes (a key precursor for the production of polyester fibres and polyethylene terephthalate) will account for around 26% of the total annual capacity of the complex (8.8 million tonnes per annum), ethylene will account for roughly 13% of the total annual capacity (4.2 million tonnes per annum), and benzene will account for around 8% (2.5 million tonnes per annum) of the total annual capacity.[31]

Another notable example can be found at the Yanbu refinery in Saudi Arabia, a joint venture between oil company, Saudi Aramco, and petrochemicals manufacturer, Sabic. Upon completion, it is expected to process up to 400,000 barrels of Arabian light crude oil per day in order to manufacture 9 million tonnes of petrochemical products (approximately 45% of the site's outputs), which will include olefins, aromatics, glycols, and polymers. The Yanbu project sends an important signal to the wider global oil

29) C&EN, Why the future of oil is in chemicals, not fuels, https://cen.acs.org/business/petrochemicals/future-oil-chemicals-fuels/97/i8 [accessed June 2023].
30) McKinsey, From crude oil to chemicals: How refineries can adapt to shifting demand, https://www.mckinsey.com/industries/chemicals/our-insights/from-crude-oil-to-chemicals-how-refineries-can-adapt-to-shifting-demand [accessed June 2023].
31) Offshore Technology, Petrochemicals complex profile: Zhejiang Petrochemical Daishan Complex, China, https://www.offshore-technology.com/marketdata/zhejiang-petrochemical-daishan-complex-china/ [accessed June 2023].

industry, as it represents the view of Saudi Aramco, the world's largest oil producer, that the future of oil is moving towards petrochemicals.[32]

3 Petrochemical Sustainability Transition

Petrochemicals currently account for around 12% of global oil demand. But by 2030, it is anticipated that the production of chemicals will become the single largest driver of oil consumption globally.[33] Not only are fossil fuels used as the primary feedstocks for the production of petrochemicals, but they are also used to generate the energy, heat and pressure required during the manufacturing processes employed. As a result, industrial chemistry's use of petroleum and natural gas accounts for approximately 6% of all greenhouse gases (GHGs) emitted globally.[34] Therefore, as part of a wider move towards a global economy based on renewable energy, a reduced dependence on finite fossil fuels, and less GHGs emitted to the atmosphere, it is a key aim of the chemical industry to minimise process emissions and to improve the overall sustainability of the sector.

In order to boost the sustainability of chemicals manufacturing, there are a number of changes that can be made to both the products and processes that traditionally depend upon the use of oil and gas. The first of which would be to employ renewable energy in place of fossil-derived fuels during chemical manufacturing processes. Not only would this reduce the CO_2 emissions associated with production, but it would also lessen industry's dependence on the use of fossil fuels associated with geopolitical risks, thus improving the overall energy security of the sector.[35] Combined with the implementation of newer, more energy efficient processes (in order to use less energy overall) and the employment of carbon capture utilisation and/or storage (CCUS) technologies (to capture/remove any CO_2 generated by the process), and there is a huge opportunity to minimise GHG emissions and to improve the overall sustainability of chemicals manufacturing.[36]

While process energy can be decarbonised through the use of renewable energy, the fundamental behind the petrochemical industry is the use of carbon molecules as raw materials to produce chemicals and polymers. Therefore, it is not possible to decarbonise chemical products in the way that it is possible to decarbonise energy. In this regard, industry should consider de-fossilising rather than decarbonising chemicals, in order to reduce the sector's dependence on fossil resources (coal, crude oil and natural gas), and to lower the associated GHG emissions of chemical products.

One option for the de-fossilisation of chemicals is the use of sustainable, renewable biomass as an alternative source of carbon. Biomass sequesters carbon from the atmosphere, and this carbon can then be used to make chemicals and materials. Removing CO_2 from the air, means that any products derived from biomass generally have lower associated GHG emissions than their fossil-based counterparts. This is especially true if bio-based chemicals are used to manufacture long-lasting products, whereby

32) C&EN, Why the future of oil is in chemicals, not fuels, https://cen.acs.org/business/petrochemicals/future-oil-chemicals-fuels/97/i8 [accessed June 2023].
33) IEA, The Future of Petrochemicals, https://www.iea.org/reports/the-future-of-petrochemicals [accessed June 2023].
34) Climate Watch, the World Resources Institute (2020), Global greenhouse gas emissions by sector (2016)
35) IEA, Contribution of Renewables to Energy Security, https://www.iea.org/reports/contribution-of-renewables-to-energy-security [accessed June 2023].
36) CEFIC, https://cefic.org/a-solution-provider-for-sustainability/chemistrycan/going-climate-neutral/producing-chemicals-with-100-renewable-energy/ [accessed June 2023].

atmospheric carbon can be locked away for longer periods of time – thus, having potentially beneficial effects in the fight against climate change.[37]

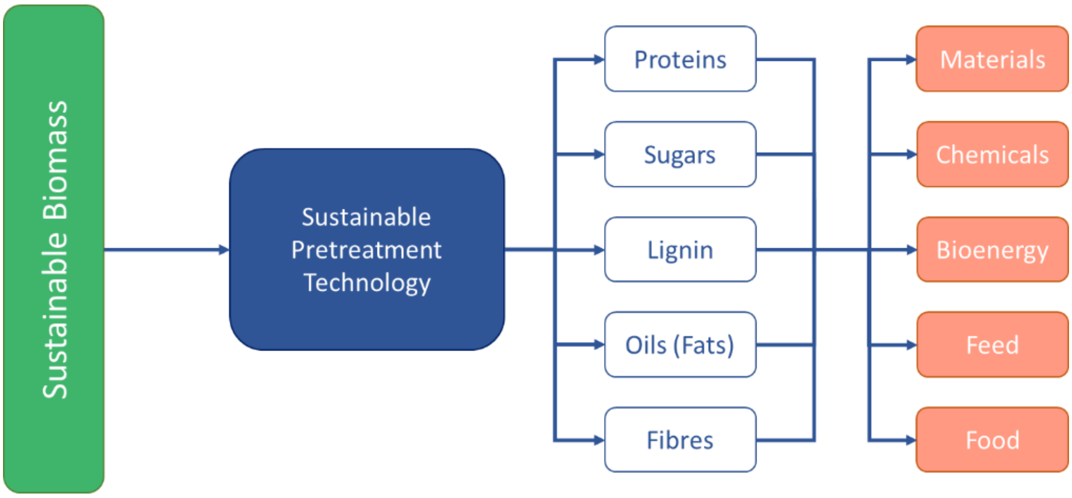
Bio-based feedstocks can range from dedicated energy crops, agricultural crop residues, forestry residues, algae, wood processing residues, municipal solid waste (MSW) and commercial and industrial (C&I) wastes.[38] Feedstocks can inevitably vary in composition based on a range of factors including feedstock type, environmental factors, harvesting practices, storage conditions, and pre-processing techniques. This allows for a wide selection of differing feedstock configurations which can be tailored towards the production of various chemicals and products downstream.[39]

Chemicals manufactured through the use of bio-based feedstocks may be chemically identical to their petroleum counterparts (otherwise known as drop-in chemicals), or they may be new-to-market bio-based chemicals. Drop-in chemicals are bio-based versions of existing petrochemicals which have established markets and recognised end-user products. Key examples include ethylene, propylene, acetic acid, acrylic acid, butadiene, isobutanol and succinic acid. New-to-market bio-based chemicals on the other hand, are chemicals which are produced *via* a novel pathway and which do not have an identical fossil-based counterpart. As such, they can be used to produce products that cannot be obtained through traditional chemical reactions and can offer unique and superior properties that are unattainable with fossil-based alternatives. Key examples of new-to-market bio-based chemicals include: itaconic acid, furans (e.g., HMF, furfural and FDCA), levulinic acid, sorbitol, xylitol, bio-based lubricants and surfactants (e.g., sophorolipids and rhamnolipids), and cellulose fibres (e.g., nanocellulose and microcellulose).[40]

Biomass is typically made up of a range of components (including starches, sugars, cellulose, hemicellulose, lignin, fats, proteins and ash for example) which can vary in their quantities depending on the feedstock type, as well as on a range of external factors. Much like a traditional petrochemical refinery, which separates out the various components of crude oil so that they can be used in different applications downstream, it is also possible to convert biomass feedstocks into a spectrum of useful fractions in order to produce a variety of high-value chemicals and fuels. This is referred to as a biorefinery (Figure 9).

37) European Commission, Communication from the commission to the European Parliament and the council,https://climate.ec.europa.eu/system/files/2021-12/com_2021_800_en_0.pdf [accessed June 2023].
38) US Government, Biomass Resources, https://www.energy.gov/eere/bioenergy/biomass-resources [accessed June 2023].
39) Energy Technologies Institute, Understanding Variability In Biomass Feedstocks And The Opportunities For Pre-Processing, https://d2umxnkyjne36n.cloudfront.net/insightReports/3752-Biomass-Feedstocks-Insight-v6-002.pdf?mtime=20180321164208 [accessed June 2023].
40) Renewable Carbon News, https://renewable-carbon.eu/news/gaining-momentum-bio-based-polymers-grow-at-a-cagr-of-14-between-2022-and-2027/ [accessed June 2023].

Figure 9: Example overview of the biorefinery concept whereby sustainable biomass is fractionated into constituent parts in order to generate a range of potential chemicals, materials, energy, fuel, food and/or feed etc.



Combining green chemistry principles[41] with the complete valorisation of feedstocks as part of a biorefinery process, and the generation of bioderived chemicals generally offers a much greener and more sustainable alternative to traditional petrochemical manufacturing. However, in order for this to truly be the case, the bio-based feedstocks themselves must be considered sustainable. This means that:[42]

- the lifecycle GHG emissions of all feedstocks must be taken into account;
- land use must not compete with land previously destined for food and feed markets;
- the use of waste/residue feedstocks are preferred over the use of virgin biomass;
- the use of biomass from ancient or protected forests/ecosystems must be strictly avoided;
- biomass should be regenerated in order for it to be considered a renewable feedstock and to facilitate carbon sequestration from the environment.

Although biogenic carbon is considered the main alternative to fossil-derived carbon when looking to generate more sustainable chemicals in the near term, CO_2 from carbon-capture and utilisation technologies is another potential carbon source for the future. In this instance, carbon would be taken from the air or captured from an industrial process and converted to create chemical products. At present however, high costs of CCUS technologies currently prohibit the large scale roll out of CO_2 based chemicals.[43]

Furthermore, the use of recycled carbon should also be taken advantage of when looking to generate more sustainable chemicals in the future. Recycled carbon refers to the carbon embedded in existing products which can be recovered and reused following material recycling (e.g., plastics recycling). It is estimated that global chemical demand could be reduced by as much as 23-33% if effective circularity

41 Green chemistry principles include developing more energy efficient processes; using renewable energy to power said processes; using greener, more environmentally friendly solvents; and minimising waste for example.

42) CCC, Biomass in a Low Carbon Economy, https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf [accessed June 2023].

43) Global CCS Institute, Technology Readiness And Costs Of CCS, https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf [accessed June 2023].

interventions and recycling measures are implemented around the world.[44] This highlights the sheer importance of utilising recyclates as carbon feedstocks for the production of chemicals. However, it is also necessary that fresh carbon will still need to enter the material cycle in order to feed the overall growth of the global chemical industry, and to compensate for inevitable recycling losses.

The global chemical sector is under pressure to re-evaluate its dependence on imported crude oil and natural gas as raw materials, and to undergo a carbon transition based on the utilisation of more sustainable feedstocks. Industry observers agree that there is a need to accelerate innovation, enable early investment, support lower GHG generating technologies, overcome barriers to circular economy solutions, and to ensure that companies can access the large amounts of clean electricity and other inputs/infrastructure that they may need. The products arising from the chemical industry underpin our way of life. They are present in healthcare, packaging, agriculture, textiles, automotive components and construction. Therefore, unless the chemical sector transitions to a more sustainable model of operation, it will be challenging for other areas of the global economy to be considered truly sustainable in the future as a result.[45]

4 Global Bio-based Chemical Production

As outlined in the previous chapter, biogenic carbon is recognised as being the main alternative to fossil-derived carbon when looking to reduce the chemical industry's dependence on finite crude oil and natural gas. At present, the global production of bio-based chemicals is estimated to be in the region of around 90 million tonnes per annum,[46] a figure that is anticipated to increase considerably over the next few decades as the global demand for chemicals is set to rise and the demand for more environmentally friendly products is set to grow.

The top 10 bio-based chemicals currently generated around the globe are highlighted in Table 17. Bioethanol is by far the most mature bio-based chemical manufactured today, representing more than 80% of the overall market in terms of production. It is primarily used as a transport fuel, but it is also used for the synthesis of bio-based ethylene, ethylene oxide, monoethylene glycol (MEG), and a range of other products. The global bioethanol market is dominated by two countries – the US (accounting for roughly 55% of the market) and Brazil (accounting for roughly 26% of the market).[47] In addition to the top 10 chemicals highlighted in Table 17, a myriad of others, whether bulk or speciality, also play a key role in contributing to the global bio-based chemical market.

Table 17: Top 10 bio-based chemicals in terms of global capacity (kta).[48]

Chemical	Global Capacity (kta)	Uses

44) Planet-compatible pathways for transitioning the chemical industry https://www.pnas.org/doi/10.1073/pnas.2218294120 [accessed June 2023].
45) Systemiq, Planet Positive Chemicals, https://www.systemiq.earth/wp-content/uploads/2022/10/Main-report-v1.22.pdf [accessed June 2023].
46) IEA, Bio-based Chemicals, https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf [accessed June 2023].
47) Statista, Ethanol Production https://www.statista.com/statistics/281606/ethanol-production-in-selected-countries/ [accessed June 2023].
48) IEA, Bio-based Chemicals, https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf [accessed June 2023].

Ethanol	80,800	Transport fuel, production of ethylene, ethylene oxide, and MEG
Citric acid	2,000	Used as an acidulant, preservative, emulsifier, flavouring, chelating and buffering agent in food, beverage, pharmaceutical, nutraceutical and cosmetic products.
Sorbitol	1,800	Used primarily in food. Raw material for surfactants and polyurethane foams. Used to produce ascorbic acid, sorbitan, isosorbide, and 1,2-propanediol.
Glycerol	1,500	Used in wound and burn treatments, as a sweetener in the food industry, and as a humectant in pharmaceutical formulations
Lysine	1,100	Essential amino acid, used as a food and feed supplement
Syngas	760	Use as a fuel, as a source of hydrogen, to reduce iron ore to sponge iron, for the production of methanol, ammonia and oxo alcohols
Lactic acid	600	Preservative and pH adjusting agent in the food and beverage sector. Used as a solvent and starting material in the production of lactate ester. Used as active ingredient in personal care products. For the production of polylactic acid (PLA).
Epichlorohydrin	540	Production of epoxy resins, and other resins and polymers
Furfural	360	Production of furfuryl alcohol, tetrahydrofuran and levulinic acid
Ethylene	200	Production of HDPE, LDPE, PVC and PET

From a technical point of view, any petrochemical currently manufactured using fossil-derived feedstocks can in theory be generated using biogenic resources as alternative starting materials. However, at present, the cost of producing bio-based chemicals in many cases exceeds the cost of manufacturing petrochemical equivalent products. The low price of crude oil over recent decades has thus, in effect, restricted the bio-based drop-in chemical market's potential for growth. However, this is anticipated to change as price volatility becomes more commonplace for oil and gas resources (typically caused by changes in supply and demand, natural disasters, production costs, and political instability e.g., note the ongoing conflict in Ukraine).

Given that bio-based chemicals have not traditionally been able to compete with identical petrochemical compounds on the market, industry has therefore largely focussed on the development of new-to-market products that offer novel functionalities with often enhanced properties and lower environmental impacts compared with established petrochemical alternatives. In these cases, the desirable attributes of said compounds in many ways justifies their elevated price points on the market. Some of the most promising of these which have the potential to make an impact on the industry in the future, are highlighted below:[49]

- **2,5-furandicarboxylic acid** – Can be used to make polymers such as PEF, a stronger alternative to PET. It is a fibre used to make plastic bottles, food packaging and carpets.
- **Levoglucosenone** – A safer alternative to harmful solvents used in pharmaceutical manufacturing. Also used in flavours and fragrances.
- **Muconic acid** - Derivatives could replace non-sustainable chemicals used in the production of PET and nylon fibres.

49) UKBiochem10, http://ukbiochem10.co.uk/ [accessed June 2023].

- **Itaconic acid** – A replacement for petroleum based acrylic acid, used to make absorbent materials for nappies, as well as resins for use in high-performance marine and automotive components.
- **1,3-butanediol (1,3-BDO)** – A building block for many high-value products including: pheromones, fragrances, insecticides, antibiotics and synthetic rubber.
- **Glucaric acid** – Prevents deposits of limescale and dirt on fabric or dishes, providing a green replacement for phosphate-based detergents.
- **Levulinic acid** – Used in the production of environmentally friendly herbicides, flavours and fragrances, skin creams and degreasers.

While these compounds can be exploited for their novel functionalities, enhanced properties and lower environmental impacts, they are not typically generated in bulk quantities at present due to the costs associated with their production. As has been previously highlighted in this report, one way of maximizing the valorisation of biological feedstocks, in order to generate bio-based chemicals with lower overall costs, is through the use of integrated biorefineries.

Roughly 1,300 biorefineries have been identified around the world, with approximately half of these found in the United States alone. The main type of feedstock used within these biorefineries is primary biomass (e.g., starch crops, oil crops, sugar crops, and lignocellulosic biomass from crop land/grass land/forestry etc.), followed by secondary biomass (e.g., agricultural residues and forestry residues). The biochemical conversion of biomass is the most common type of processing technology used by the world’s biorefineries (e.g., fermentation), followed by chemical conversion (i.e., catalytic conversion, esterification, and hydrogenation), and mechanical and thermo-chemical conversion technologies (e.g., extraction, separation, gasification, and pyrolysis).[50]

Figure 10 outlines the estimated proportion of products that are generated by biorefineries around the world. It highlights that energy is the primary output of a typical integrated biorefinery, followed by chemicals (e.g., chemical building blocks, and pharmaceutical/nutraceutical ingredients) and materials (polymers and fibres).

50) IEA, Bioenergy Task 42, https://www.ieabioenergy.com/wp-content/uploads/2022/09/IEA-Bioenergy-Task-42-Global-biorefinery-status-report-2022-220712.pdf [accessed June 2023].

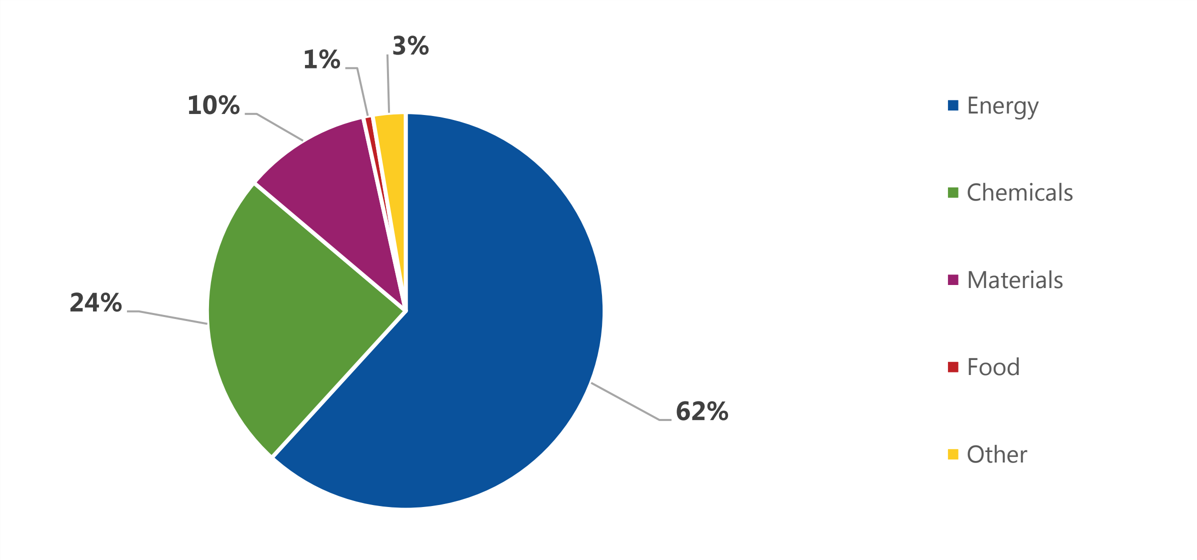


Figure 10: Main biorefinery product types manufactured globally (based on the percentage of plant numbers generating the specified outputs).[51]

The generation of energy and fuels alongside the production of chemicals and materials typically allows for bio-based products to be manufactured more cost competitively with an integrated biorefinery, rather than with a dedicated single product production process. Many state-of-the-art biorefineries exist around the world to generate bio-based chemicals and materials, however various challenges still remain when looking to scale-up novel and more advanced production processes, both from an economic and technical point of view.[52] Furthermore, the use of second-generation biomass as feedstocks (i.e., lignocellulosic biomass) within a biorefinery also requires further development, due to the recalcitrance and complexity of these types of materials. More efficient pre-treatment processes are still needed to sufficiently separate and valorise the individual components within these feedstocks.

In order to completely transition from a chemical industry based on the use of fossil-derived feedstocks to one based on biogenic resources, it is clear that there needs to be a profound revision of existing industrial processes and technologies, as well as major investment into the sector, and the implementation of constructive governmental policy incentives.[53]

5 Bio-based Chemical Carbon Emissions

Bio-based chemicals are perceived to be more environmentally sustainable than petrochemical alternatives because they are produced from renewable, biogenic resources. Biomass sequesters carbon from the atmosphere, and this carbon can then be used to make chemicals and materials downstream. The use of biogenic feedstocks as a replacement for fossil resources offers the possibility for reduced

51) IEA, Bioenergy Task 42, https://www.ieabioenergy.com/wp-content/uploads/2022/09/IEA-Bioenergy-Task-42-Global-biorefinery-status-report-2022-220712.pdf [accessed June 2023].
52) https://www.frontiersin.org/articles/10.3389/fchem.2022.973417/full [accessed June 2023].
53) Gerardy. R., et al., Continuous Flow Upgrading of Selected C2–C6 Platform Chemicals Derived from Biomass, 2020, https://pubs.acs.org/doi/abs/10.1021/acs.chemrev.9b00846 [accessed June 2023].

fossil based GHG emissions.[54] However, in reality this may not always be the case and thus, their associated environmental impacts should be confirmed using life cycle analysis (LCA).

In order to effectively compare the carbon emissions associated with bio-based chemicals with the carbon emissions of similar petrochemicals, LCA studies must be carried out on the products themselves and their accompanying manufacturing processes. The main issue here, however, is that a limited number of LCAs are currently available for bio-based chemicals at relevant industrial scales (key examples at present include succinic acid, lactic acid, 1,4-butanediol and 1,3-propanediol). The majority of other LCA studies carried out for other bio-based chemicals typically rely on the use of data obtained at demonstration, pilot, or even lab-scales.[55] In order for LCAs to paint a realistic picture of the impacts associated with bio-based chemicals, the data used should therefore aim to be representative of genuine industrial production and use.[56]

Furthermore, it can also be difficult to accurately compare LCA results from different studies performed on the same chemicals – a consequence of employing different LCA methodologies and assumptions, as well as the use of different scopes and data collection techniques. In general, the results obtained from different LCA studies can be rarely compared due to these variables and so, drawing accurate conclusions from published LCAs is not as straightforward as it may seem. That does not mean however, that general trends in GHG emissions cannot be identified. For example, several review papers have shown that the production of bio-based products have the potential to significantly reduce GHG emissions and the use of fossil resources across the global chemical industry (e.g., relative to their petroleum-derived counterparts, bio-based succinic acid,[57] bio-based ethanol,[58,59] lactic acid[60] and polylactic acid[61] can all exhibit significant GHG reductions and a reduction in the use of finite fossil resources).

Furthermore, the EU's Joint Research Centre (JRC) commissioned a study on the "Environmental impact assessments of innovative bio-based products", covering seven cradle-to-grave LCA case studies for three commercialised bio-based polymers (bio-based polyethylene terephthalate (PET); polylactic acid (PLA); and starch plastics). The primary data used for this study was gathered from industry, based on real existing supply chains and on feedstocks currently used by the sector at present. The aim of this

54) OECD, Industrial Biotechnology & Climate Change, https://www.oecd.org/science/emerging-tech/49024032.pdf [accessed June 2023].
55) Ögmundarson. O., Life Cycle Assessment of chosen Biochemicals and Bio-based polymers, https://orbit.dtu.dk/en/publications/life-cycle-assessment-of-chosen-biochemicals-and-bio-based-polyme [accessed June 2023].
56) Greenhouse Gas Protocol, Product Life Cycle Accounting and Reporting Standard, https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf [accessed June 2023].
57) J., De Meester, S., Alvarenga, R.A.F. (Eds.), Sustainability Assessment of Renewables-Based Products: Methods and Case Studies. Wiley. pp. 307–322. ISBN: 978-1-118-93394-7.
58) Jeswani, H.K., et al., 2015. Life cycle environmental sustainability of lignocellulosic ethanol produced in integrated thermo-chemical biorefineries. Biofuels Bioprod. Bioref. 9:661-676.
59) Muñoz, I., et al., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int. J. Life Cycle Assess. 19:109-119.
60) Morales, M., et al., 2015. Environmental and economic assessment of lactic acid production from glycerol using cascade bio- and chemocatalysis. Energy Environ. Sci. 8:558-567.
61) Vink, E.T.H., et al 2015. Life Cycle Inventory and Impact Assessment Data for 2014 Ingeo™ Polylactide Production. Indus. Biotechnol. 11:167-180.

study was to provide reliable evidence on the environmental impacts associated with the production and use of novel bio-based products. Key conclusions include:[62]

- The generation of bio-based feedstocks typically requires more land than is needed for the extraction and processing of fossil fuels. Thus, land use and associated impacts for bio-based products are generally higher than for fossil-derived products. However, said impacts are understood to be minor compared to the impacts associated with product manufacturing.
- The manufacturing phase of a product's life cycle accounts for approximately 50% of all cradle-to-grave impacts in each of the case studies reviewed.
- The impact of transport on a product's life cycle is generally insignificant (except for when the global supply chain is exceptionally long).
- The end-of-life of bio-based products can vary considerably depending on the end-use application. Thus, the impacts associated with end-of-life were difficult to establish.

When comparing the seven case studies on bio-based polymers with their petrochemical counterparts, all seven demonstrated environmental benefits in terms of GHG savings. However, all seven case studies on the bio-based polymers also showed higher volumes of particulate matter generation compared with petrochemical counterparts.[63] This is important to recognise, that while bio-based products can lead to lower GHG emissions compared with fossil-derived alternatives, they may have negative impacts elsewhere. Hence why the performance of comprehensive LCAs for novel bio-based products is necessary.

At present, the bio-based chemical sector remains an emerging industry and as such, many associated production processes have not yet been fully optimised for efficiency. Furthermore, the scale of many bio-based chemical production processes is generally much smaller than seen for petrochemical production, which therefore minimises the benefits associated with economies of scale. In the future however, through process optimisation and decarbonisation of the global energy sector, it is anticipated that the carbon emissions associated with bio-based chemical production will decrease further, beyond what is possible today. Moreover, the majority of LCA studies available for bio-based chemicals at present focus on the use of first-generation sugars as feedstocks (from sugarcane, sugar beet or corn starch for example), as opposed to second or third-generation feedstocks which have the potential to reduce GHG values further (as land use impacts can be minimised).[64]

Traditional petrochemical production processes are also expected to become more efficient over time and thus, could be associated with lower GHG emissions in the future. However, overall, it is anticipated that life-cycle data will become less favourable towards the production of petrochemicals going forward as fossil fuel extraction/upgrading is set to become more difficult and thus, more energy intensive. New oil and gas exploration methods (e.g., tar sands, deep sea drilling, arctic exploration etc.) as well as the

62) European Commission, Environmental impact assessments of innovative bio-based products, https://op.europa.eu/en/publication-detail/-/publication/9ab51539-2e79-11e9-8d04-01aa75ed71a1 [accessed June 2023].
63) European Commission, Environmental impact assessments of innovative bio-based products, https://op.europa.eu/en/publication-detail/-/publication/9ab51539-2e79-11e9-8d04-01aa75ed71a1 [accessed June 2023].
64) IEA, Bio-based Chemicals, https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf [accessed June 2023].

extraction of heavier and more contaminated oil, will cause ongoing challenges for the petrochemical industry when looking to keep associated GHG emissions in line with existing processes.[65]

In general, it can be alluded that the GHG emissions associated with bio-based chemicals are lower than for traditional petrochemicals, a statement that is expected to be the case even more so in the future. In order to validate the sustainability and GHG emissions linked to bio-based chemicals, accessible and transparent data must be collected and provided by the chemical industry in order for reliable LCA studies to be carried out. Furthermore, a robust set of data for petrochemical counterpart should be made available in order to make effective comparisons with novel bio-based alternatives. The European Committee for Standardization (CEN) has provided clear guidance on how to conduct an LCA for bio-based products.[66, 67] These approaches should be used in the future to assess the overall environmental performance of bio-based chemicals and materials, and to compare against fossil-based counterparts.

6 Chemical Production in the UK

The chemical industry is the second largest manufacturing sector in the UK (behind machinery and transport equipment) accounting for over £54bn in exports and £30.7bn in value added to the UK economy in 2021. The UK's chemical and pharmaceutical industry has a workforce of over 140,000 people, and it is understood that a further 350,000 jobs are also supported across sector associated supply chains. Approximately 4,535 chemical companies operate throughout the UK, with manufacturing sites located in all regions of the country. Commodity chemicals are primarily produced in Scotland and Northern England and use hydrocarbon feedstocks (mainly natural gas and refined petroleum fractions), as well as minerals, vegetable oils, and animal-derived oils/fats as feedstocks. More specifically, the North West is the UK's leading producer of chemicals, followed by Scotland, the North East, and Yorkshire & the Humber regions.[68]

Despite having experienced covid-19 related lockdowns, severe trade friction, and soaring raw material prices in recent years, the UK's chemical industry has benefitted from an upsurge in demand for pharmaceuticals and personal care products and was boosted by the stockpiling of goods prior to the end of the Brexit transition period, which further increased the nation's demand for chemicals.[69] As such, the UK's chemical outputs increased by 5.3% in 2020 and by 3.7% in 2021, one of the only industries to experience growth during this period. Since then, UK chemical production entered 2022 at near record production highs. However, elevated energy prices (largely caused by Russia's invasion of Ukraine), coupled with labour and raw material shortages, led to a general downturn in productivity during 2022. Therefore, as a result, chemical outputs in September 2022 were 11.7% lower than in January 2022

52) IEA, Bio-based Chemicals, https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf [accessed June 2023].
66) CEN-EN 16760 Biobased products - Life Cycle Assessment. 2015. European Committee for Standardization (CEN), https://standards.globalspec.com/std/9972876/EN%2016760. [accessed June 2023].
67) CEN-EN 16760 Biobased products - Life Cycle Assessment. 2015. European Committee for Standardization (CEN), https://standards.globalspec.com/std/9972876/EN%2016760. [accessed June 2023].
68) CEFIC, https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/united-kindgom/ [accessed June 2023].
69) Chemical Industries Association, https://www.cia.org.uk/Portals/0/Documents/CIA%20Q4%202022%20Economic%20Report_.pdf [accessed June 2023].

(although still above pre-pandemic levels), and the Chemical Industries Association (CIA) forecasts that UK chemical production will continue to fall throughout 2023.[70]

Key strengths of the UK's chemicals sector include:[71]

- Heightened political recognition and value, driven by the industry's importance to the economy and wider society in the fight against Covid-19. As such, this has also significantly improved the public's perception of the sector.
- The chemical industry is able to contribute to a wide range of areas, including basic inorganics, petrochemicals, polymers, agrochemicals, paints, detergents, personal care products, adhesives, flavours and fragrances, lubricants, fuel additives, construction chemicals, and catalysts.
- The sector benefits from several closely integrated clusters (e.g., Grangemouth, Teesside, Merseyside, Humberside, South Wales, and Southampton) and makes use of an extensive ethylene pipeline network.
- The UK has ethane import infrastructure, and three steam crackers that are able to use ethane as a feedstock to generate ethylene.
- The UK has strong export links to geographically diverse markets.
- The sector is highly innovative, backed by exceptional research and university infrastructure. This has also resulted in a strong pool of highly skilled researchers and staff.

Despite the clear strengths of the UK's chemical industry, the sector faces a number of near, medium and long-term challenges. A major challenge lies in issues caused by Brexit.[72] For example, there has been ongoing disruption linked to Brexit and medium to long-term investment in the sector as a result. Uncertainty has arisen around the design and implementation of the UK's version of REACH (registration, evaluation, authorisation and restriction of chemicals), the primary law within the EU to protect human health and the environment from the risks posed by chemicals.[73] The historic strength of the UK's chemical sector in supplying to key customer industries (e.g., aerospace and automotive) is now challenged by ongoing Brexit disruption and stronger growth in non-European markets. Furthermore, there is a scarcity of skilled craft workers because of an aging workforce, because of competition from other sectors and because of a lack of labour following Brexit.[74]

The most prominent challenge currently facing the UK's chemical sector however lies in the current cost of crude oil and natural gas. Unlike other industries, fossil fuels are not just utilised as an energy source in the chemicals sector, but also as feedstocks for the production of petrochemicals. This, therefore, intensifies the industry's exposure to rising oil and gas prices, which has ultimately been caused by

70) CEFIC, https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/united-kindgom/ [accessed June 2023].
71) CEFIC, https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/united-kindgom/ [accessed June 2023].
72) Chemical Industry Journal, Report suggests Brexit could hit UK chemicals industry hard, https://www.chemicalindustryjournal.co.uk/report-suggests-brexit-hit-uk-chemicals-industry-hard [accessed June 2023].
73) Chemistry World, UK Reach costs stretch higher for industry, https://www.chemistryworld.com/news/uk-reach-costs-stretch-higher-for-industry/4016041.article [accessed June 2023].
74) CEFIC, https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/united-kindgom/ [accessed June 2023].

Russia's invasion of Ukraine.[75] Alongside these direct impacts on energy/feedstock costs, the UK's chemical industry has also been indirectly impacted by:

- A decrease in chemical demand – households are spending considerably more of their disposable income on energy, leaving less to be spent on products derived from the chemicals sector.[76]
- An increase in competition – the cost of energy in China for example, is roughly 6 times cheaper than energy in Europe, meaning that chemicals can be produced more cost effectively and sold for a more competitive price on the market compared to UK derived products.[77]

In looking to mitigate the direct and indirect issues caused by high energy and feedstock prices, it is important for the sector to adapt in order to move forward. One way of avoiding these impacts, would be through the use of renewable energy in place of fossil fuels, and the use of renewable biomass as carbon feedstocks. Not only would this improve energy/feedstock security by reducing the industry's reliance on Russian oil and gas, but it would also encourage the industry to work towards net zero targets.[78]

The UK's 'net zero target' refers to a government commitment to ensure that the UK reduces its greenhouse gas emissions by 100% from 1990 levels by 2050. If met, this would mean that the amount of greenhouse gas emissions produced by the UK would be equal to or less than the total emissions removed from the atmosphere annually in the UK.79 The UK's chemical industry is currently a notable emitter of GHGs.

Figure 11 illustrates the main chemical clusters in the UK and the industrial emissions associated with these. In the quest towards achieving net zero, by deviating away from the use of traditional fossil fuels for the production of chemicals, the emissions associated with the sector thus have the potential to decrease and contribute towards said targets.

75) AGChemigroup, Energy Prices and their Impact on Chemical Production, https://blog.agchemigroup.eu/energy-prices-and-their-impact-on-chemical-production/ [accessed June 2023].
76) ICIS, https://www.icis.com/explore/resources/news/2022/12/29/10839977/insight-outlook-23-global-chemical-operating-rates-plunge-to-2008-9-levels-braced-for-storms-ahead/ [accessed June 2023].
77) UK Parliament, Exiting the European Union, https://www.parliament.uk/globalassets/documents/commons-committees/Exiting-the-European-Union/17-19/Sectoral-Analyses/7-Sectoral-Analyses-Chemicals-Report.pdf [accessed June 2023].
78) IEA, Chemicals, https://www.iea.org/reports/chemicals [accessed June 2023].
79) House of Lords Library, Mission zero: Independent review of net zero, https://lordslibrary.parliament.uk/mission-zero-independent-review-of-net-zero/#:~:text=The%20'net%20zero%20target'%20refers,the%20UK%20from%20the%20environment. [accessed June 2023].

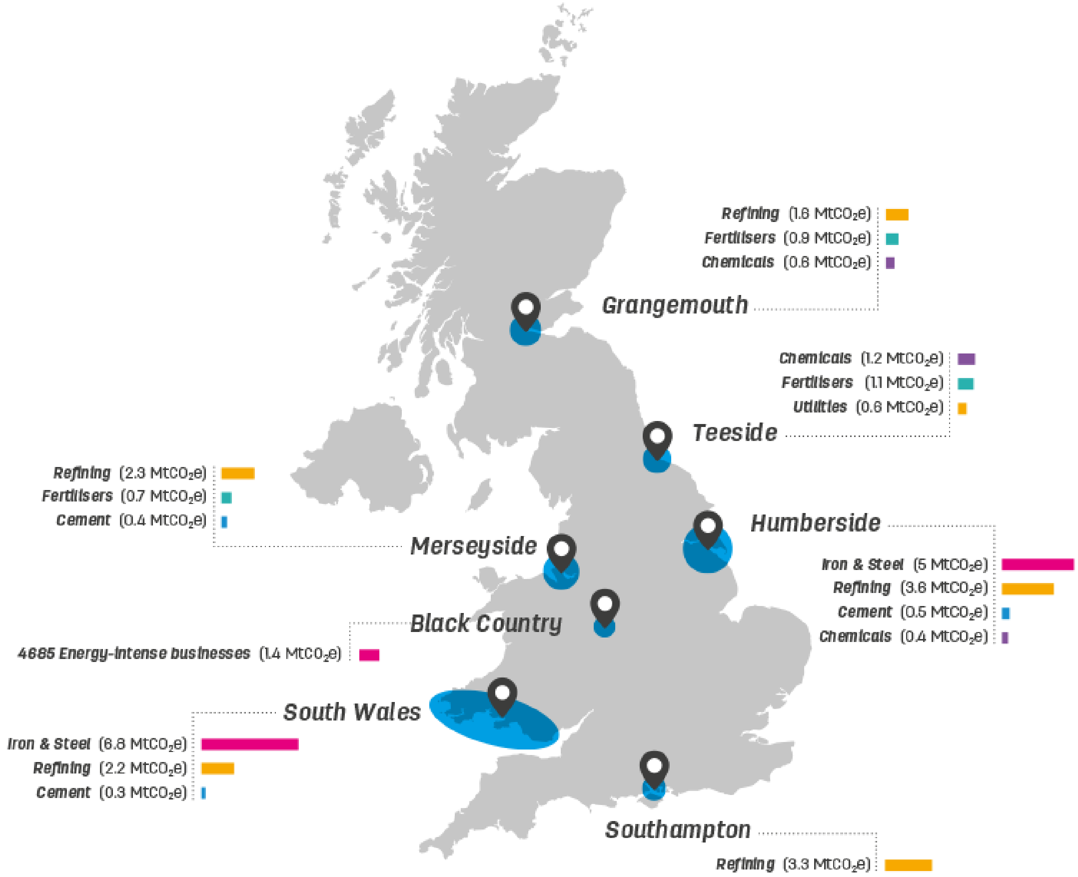


Figure 11: Industrial emissions generated by the UK's largest manufacturing clusters (including chemicals).[80]

7 UK Biomass and Land Availability

If the UK chemical industry was to transition to more widespread use of biogenic feedstocks over the use of oil and gas, it is imperative to ensure that sizable amount of biomass can be supplied domestically to avoid the need to import. Biogenic feedstock options used by biorefineries around the world include starch crops (e.g., wheat and maize), sugar crops (e.g., beet and cane), perennial grasses and legumes (e.g., ryegrass and alfalfa), lignocellulosic crops (e.g., managed forest, short rotation coppice, switchgrass), lignocellulosic residues (e.g., forest residues, stover and straw), oil crops (e.g., palm and oilseed rape), aquatic biomass (e.g., algae and seaweeds), and organic residues (e.g., industrial, commercial and postconsumer waste). Of course, the availability of certain types of biomass in regions around the world depends largely on geography. In the UK, key sources of biomass which could be used to feed a future bio-based chemical industry include:

- Cereal crops (e.g., wheat, barley, oats, oil seed rape) & cereal crop residues;
- Sugar beet & sugar beet pulp;
- Forestry biomass & forestry residues.

80) UK Industrial Clusters Decarbonisation, https://zerocarbonhubs.co.uk/industrial-clusters.html [accessed June 2023].

- Perennial ryegrass;
- Industry residues

There are roughly 24.2 million hectares of land in the UK. It is understood that the total agricultural area in the UK is around 17.6 million hectares, with an additional 3.2 million hectares covered by woodland and forests. The agricultural area, excluding woodland, accounts for 72% of total UK land. Approximately 40% of total UK land is permanent grass land, 20% is arable cropping, 13.1% is broadleaf woodland, 6% is temporary grass land, 5.9% is built-on land, 5% is rough grazing, 2% is green urban land, 1% is non-agricultural land, and 6% is other land (i.e., marches, rocks, beaches, dunes etc.).[81]

In terms of cereal crop production in the UK, average annual wheat production is approximately 15 million tonnes, average annual barley production is approximately 7 million tonnes, while for oats, annual production is around 1 million tonnes, and for OSR, it is around 2 million tonnes. The current 5-year average for wheat yields in the UK is roughly 8.0 tonnes per hectare. While for barley this is 6.2 tonnes per hectare, 5.4 tonnes per hectare for oats, and 3.3 tonnes per hectare for oil seed rape. Whilst data on cereals and OSR production is publicly available, data on straw production from these crops is not. Data on crop areas and crop yields can be used to calculate total average production volumes for wheat, barley, oats and OSR. The amount of straw generated is then calculated using harvest indices (the proportion of total crop biomass that is harvested as grain) and the ratio of the remaining crop (after grain removal) that can be sustainably collected as straw was calculated (i.e., stubble/stumps of the reaped crops are typically left in the field). The total volume of straw generated in the UK between 2000-2022 is presented in Figure 12. Both cereal crops grown in the UK and their straw residues could act as possible feedstocks for the production of bio-based chemicals in the future.

81) Savills, Current Agricultural Land Use in the UK, https://www.savills.co.uk/research_articles/229130/274017-0 [accessed June 2023].

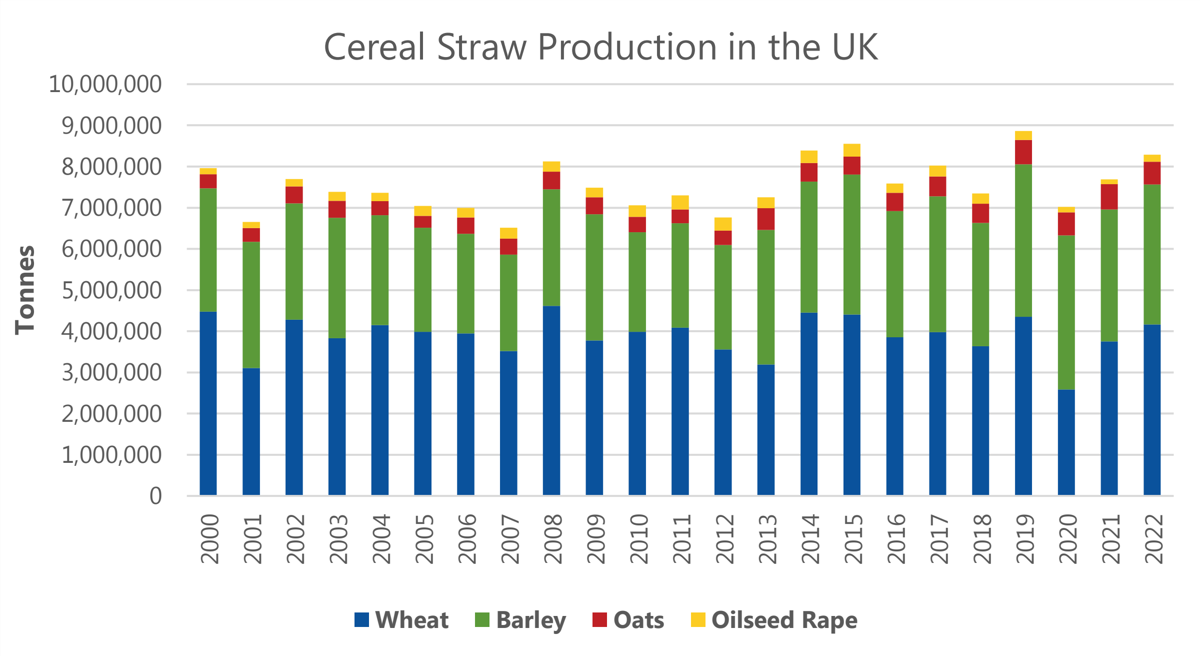


Figure 12: Total straw production in the UK (tonnes).[82]

In addition to straw residues that are generated during the production of cereal crops, it is also estimated that roughly 750,000 tonnes of wheat bran is currently produced in the UK by the wheat milling sector. A further 400,000 tonnes of oat husks are also currently generated in the UK annually.[83] These residues could also be used as feedstocks for the production of bio-based chemicals in the future.

With regards to sugar beet as potential feedstocks, currently British Sugar processes all of the sugar beets grown in the United Kingdom. British Sugar owns four factories in the UK that process sugar beet and create beet pulp, these are located in: Bury St Edmunds; Cantley; Newark; and Wissington. At Bury St Edmunds, over 2 million tonnes of sugar beet produced by over 700 growers, is processed into around 320,000 tonnes of refined sugar. Cantley processes over 1.5 million tonnes of sugar beet, produced by over 700 growers, to produce around 220,000 tonnes of refined sugar. At the Newark site, over 1.6 million tonnes of sugar beet, produced by around 700 growers, is processed to around 235,000 tonnes of refined sugar. British Sugar's fourth sugar processing facility, Wissington is the largest of all the facilities in the UK. It currently converts over 3 million tonnes of sugar beet from over 1,000 growers, to produce over 400,000 tonnes of refined sugar. In 2007, Wissington also became the location of the UK's first bioethanol plant, and this site is able to manufacture around 64,000 tonnes of ethanol per year. In total it is estimated that around 8 million tonnes of sugar beet are currently processed in the UK. While the sugar beet itself is primarily used as a feedstock for the production of sugar, the beet pulp could be a valuable feedstock for the production of chemicals. It is estimated that roughly 405,000 tonnes of sugar beet pulp are currently produced in the UK in terms of dry weight.

In terms of potential forestry derived feedstocks, in 2019, the total volume of harvested softwood was recorded as being around 9.8 million green tonnes, and the total volume of harvested hardwood was

82) NNFCC calculation based on Defra Crop Statistics, https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2022/chapter-7-crops. [accessed June 2023].
83) NNFCC calculation based on Defra Crop Statistics, https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2022/chapter-7-crops. [accessed June 2023].

recorded at around 870 thousand green tonnes. Forestry residues on the other hand are not part of UK national statistics, so the current availability of these feedstocks must be estimated from known data. An indication of forestry residue arisings can be gained from timber harvest predictions, given that forests have a defined lifetime. Wood production (also referred to as removals) refers to the harvesting of roundwood (trunk and branch wood) from coniferous (softwood) and non-coniferous (hardwood) trees. It is estimated that approximately 2.3 million tonnes of dried softwood residues are currently generated in the UK, while roughly 204,000 dry tonnes of hardwood residues are also created.

Perennial ryegrass (Lolium perenne) is a high yielding, high quality grass, and the most important forage grass species in temperate areas worldwide. As such, it is the mainstay of grassland-based agricultural systems in many areas of the world. It thrives in most soil types (except when under very dry conditions or in infertile soils) and it is the most common grass variety in the UK, primarily due to the fact that it is both a fast growing and highly resistant crop. In general, it is estimated that ryegrass production can achieve yields of around 13 tonnes of dry matter per hectare.84 Therefore, over an area of 100 hectares, roughly 7,000 tonnes of ryegrass can be expected (based on an approximate moisture content of 80wt%). The sugars contained within ryegrass are largely primarily found in the juice (as opposed to the fibre) which is estimated to be around 80wt% of the material. However, during the juicing process, not all of this liquid is successfully recovered. Therefore, assuming that only 50wt% of the feedstock is recovered as juice, this equates to roughly 3,500 tonnes of ryegrass juice generated per 100 ha of crop.

Macroalgae is another potential source of biomass available in the UK that could be potentially harnessed for the generation of bio-based chemicals in the future. Macroalgae is a collective term for seaweeds and other marine algae that are generally visible to the naked eye. They are distinguished from microalgae (e.g., diatoms, phytoplankton, and the zooxanthellae that live in coral tissue), which require a microscope to be observed. One way to classify macroalgae is on the basis of their pigmentation e.g., brown seaweed (Phaeophyceae); red seaweed (Rhodophyceae); and green seaweed (Chlorophyceae). It is estimated that around 25,000-40,000 tonnes of macroalgae (in terms of wet weight) are commercially harvested in the UK each year. This corresponds to roughly 2,000-3,000 dry tonnes of macroalgae harvested annually, for applications in food and feed products, as well as in speciality chemicals and fertilisers.

It is estimated that the UK generated roughly 40 million tonnes of commercial and industrial (C&I) waste in 2020.85 Commercial and industrial waste processing (C&I) incorporates the recycling of a wide range of waste materials, generated by all types of businesses and manufacturing processes. Those that can be considered interesting as feedstocks for a future bio-based chemical industry in the UK include biodegradable single waste streams like: paper waste (5.3 million tonnes currently arising in the UK),86 distillery wastes (roughly 4.5 million tonnes of pot ale arising in the UK, 1.9 million tonnes of draff, and

84) Perennial Ryegrass, https://www.cotswoldseeds.com/species/24/perennial-ryegrass [accessed June 2023].
85) UK Government, UK Statistics on Waste, https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste#waste-from-commercial-and-industrial-ci-activities [accessed June 2023].
86) UK Government, UK Statistics on Waste, https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste#waste-from-commercial-and-industrial-ci-activities [accessed June 2023].

3750,000 tonnes of distiller's dried grains with solubles),87 and bread manufacturing wastes for example (680,000 tonnes arising in the UK each year).88

8 Policy Landscape

In order to promote the development of a bio-based chemical industry in the UK, policy support should be utilized to encourage the advancement of novel manufacturing processes and the production of new bio-based drop-in chemicals and new-to-market products. The UK Government's principal policy for the development of a wider bioeconomy was outlined in the strategy document, "Growing the bioeconomy: a national strategy to 2030".[89] This policy was published in December 2018, but has since been repealed (publication was withdrawn in November 2021), highlighting the need for further government support in this area. This original document set out that a collective approach is needed from government, industry and the research community in order to transform the UK economy through the power of bioscience and biotechnology.

The strategy document, "Growing the UK Industrial Biotechnology Base - Enabling Technologies for a Sustainable Circular Bioeconomy: A National Industrial Biotechnology Strategy to 2030", published by four Networks in Industrial Biotechnology and Bioenergy (NIBB) in 2017, further outlined the importance of using industrial biotechnology for the production and processing materials, chemicals and energy. It recognises industrial biotechnology as an enabling technology that will underpin new manufacturing processes that are essential for delivering the Clean Growth element of the UK's wider Industrial Strategy. The report addresses: recent government, academic and industry analyses of the state of UK industrial biotechnology; the current UK IB landscape; IB investment and commercialisation; how UK IB activity compares with competitor countries; and short- and long-term recommendations to support IB and help UK global competitiveness. In order to keep pace with international competition, UK policymakers need to demonstrate foresight to develop a long-term strategic plan that places trust in UK industrial and academic expertise to grow the IB sector and the wider bioeconomy.[90]

To further drive the development of novel bio-based chemicals and materials, standards are vital so as to ensure that products are developed in a way that meet key criteria and that do not ultimately impact on the environment. As such, the government has been in consultation with industry to address "Standards for bio-based, biodegradable, and compostable plastics."[91] This demonstrates the recognition that current systems must change in order for bio-based chemicals and products to thrive on the open market. The government states that in adopting new, innovative types of plastic, it must be ensured that they are more sustainable than other alternatives. This is why Defra and BEIS published

87) NNFCC estimates
88) Bakery & Snacks, https://www.bakeryandsnacks.com/Article/2023/06/08/is-the-bakery-industry-ready-for-the-2023-food-waste-legislation#:~:text=According%20to%20food%20waste%20watchdog,concern%20%2D%20it's%20an%20environmental%20one. [accessed June 2023].
89) UK Government, Growing the Bioeconomy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1037343/181205_BEIS_Growing_the_Bioeconomy__Web_SP_.pdf [accessed June 2023].
90)Industrial Biotechnology Leadership Forum, Growing the UK Industrial Biotechnology Base, https://www.bioindustry.org/static/uploaded/d390c237-04b3-4f2d-be5e776124b3640e.pdf [accessed June 2023].
91) UK Government, Standards for biodegradable, compostable and bio-based plastics: call for evidence, https://www.gov.uk/government/consultations/standards-for-biodegradable-compostable-and-bio-based-plastics-call-for-evidence [accessed June 2023].

a call for evidence on the demand, benefit, and implications of developing standards for bio-based, biodegradable, and compostable plastics. Said document sets out a summary of responses to that call for evidence and outlines the government response by taking forward a number of policy proposals informed by the evidence received. Including further consultations on extended producer responsibility for packaging and consistent recycling collections, informing future policies aimed at tackling single-use plastic and the application of HMT's plastic packaging tax, and considering a ban on oxo-degradable plastics, subject to further evidence and a public consultation.

In order to meet critical Net Zero targets, the UK's Climate Change Committee published a report on "Land use: Policies for a Net Zero UK" which states that Net Zero requires a transformation in land use across the UK. The report sets out a detailed range of options to drive emissions reductions in England, Scotland, Wales and Northern Ireland. Including:

- Increase tree planting – increasing UK forestry cover from 13% to at least 17% by 2050 by planting around 30,000 hectares (90 – 120 million trees) of broadleaf and conifer woodland each year.
- Encourage low-carbon farming practices – such as 'controlled-release' fertilisers, improving livestock health and slurry acidification.
- Restore peatlands – restoring at least 50% of upland peat and 25% of lowland peat.
- Encourage bioenergy crops – expand the planting of UK energy crops to around 23,000 hectares each year.
- Reduce food waste and consumption of the most carbon-intensive foods – reduce the 13.6 million tonnes of food waste produced annually by 20% and the consumption of beef, lamb and dairy by at least 20% per person, well within current healthy eating guidelines.

This report outlines the importance of bio-based feedstocks and a bio-based economy in the drive towards meeting net zero emissions by 2050.

Finally, in their report on "Government policy relative to the development of the bio-based and biodegradable industries sector in the UK", the BBIA (Bio-based and Biodegradable Industries Association) examines the various UK Government strategies published since 2017 which relate to bio-based and biodegradable plastics. As an industry association, the BBIA's mission is to unite those working in biodegradable and bio-based industries and to develop partnerships, putting the bioeconomy agenda at the centre of the political debate on sustainability and economic growth in the UK. In their report, they underline the strategic support available for the production of bio-based materials in the UK and for the separate collection and treatment of certified biodegradable/compostable products post consumption. The BBIA highlights the significant development of the industry in the UK since 2017, including as a result, the funding for research driven through UKRI (UK Research & Innovation). However, this report finds that the transposition of strategic direction into policies is often contradictory and can be detrimental to the bio-based and biodegradable industries sector. Policies so far, since 2020, have been implemented which either disregard Government strategies or are announced that intend to over-turn Government strategies. The BBIA calls upon Ministers, the Civil Service and Parliamentarians, to respect the strategic trajectory laid down by Governments since 2017 when implementing policy decisions, thus supporting the industry and kick-starting major investments into the UK economy. As such, it is clear that further development is needed in this area to develop effective policies that will help to drive the bio-based chemical industry and the wider bio-based economy going forward.

9 Summary

It is estimated that the global chemical industry currently generates around $4.7 trillion in annual revenue, representing approximately 4% of global GDP, and it is responsible for the employment of over 15 million people worldwide. The global chemical market is expected to grow considerably in the coming years as developing economies continue to advance and society places greater demand on the production of affordable functional materials and products to improve the quality of lives around the world. A growth in demand for petrochemical products will mean that petrochemicals are set to account for over a third of the growth in oil demand by 2030, increasing to almost a half by 2050.

According to BP's "Energy Outlook 2023", global oil demand will plateau over the next 10 years or so, before experiencing a steady decline throughout the 2030s and beyond. The single biggest factor driving this decline in oil consumption is believed to be linked to the reduction of gasoline and diesel fuel use in road transport. With gasoline and diesel consumption waning, oil refineries must therefore look to adapt their petrochemical outputs in order to remain economically feasible in the future. Whilst the use of oil in transport is steadily on the decline, the use of oil in petrochemical production still has sufficient room to grow. Thus, crude-to-chemicals is rapidly becoming the largest driver of worldwide oil demand, and as such, petrochemical applications will soon dominate the global oil industry.

Not only are fossil fuels currently used as the primary feedstocks for the production of petrochemicals, but they are also used to generate the energy, heat and pressure required during the manufacturing processes employed. As a result, industrial chemistry's use of petroleum and natural gas accounts for approximately 6% of all greenhouse gases (GHGs) emitted globally. Therefore, as part of a wider move towards a global economy based on renewable energy, a reduced dependence on fossil resources, and less GHGs emitted to the atmosphere, it is a key aim of the chemical industry to minimise process emissions and to improve the overall sustainability of the sector.

In order to boost the sustainability of chemicals manufacturing, there are a number of changes that can be made to both the products and processes that traditionally depend upon the use of oil and gas. The first of which would be to employ renewable energy in place of fossil-derived fuels during chemical manufacturing processes. The second of which would be to de-fossilise chemical feedstocks using renewable biomass as an alternative source of carbon. Biomass sequesters carbon from the atmosphere, and this carbon can then be used to make chemicals and materials. Removing CO_2 from the air, means that any products derived from biomass can have lower associated GHG emissions than their fossil-based counterparts.

In the UK, the chemical industry is the country's second largest manufacturing sector (behind machinery and transport equipment) accounting for over £54bn in exports and £30.7bn in value added to the UK economy in 2021. Despite having experienced covid-19 related lockdowns, severe trade friction, and soaring raw material prices in recent years, the UK's chemical industry has benefitted from an upsurge in demand for pharmaceuticals and personal care products and was boosted by the stockpiling of goods prior to the end of the Brexit transition period, which further increased the nation's demand for chemicals. As such, the UK's chemical outputs increased by 5.3% in 2020 and by 3.7% in 2021, one of the only industries to experience growth during this period. Since then, elevated energy prices (largely caused by Russia's invasion of Ukraine), coupled with labour and raw material shortages, has led to a general downturn in sector productivity. The most prominent challenge currently facing the UK's chemical sector lies in the current cost of crude oil and natural gas. Unlike other industries, fossil resources are not just utilised as an energy source in the chemicals sector, but also as feedstocks for the production of petrochemicals. This, therefore, intensifies the industry's exposure to any rise in oil and gas prices.

In looking to mitigate the direct and indirect issues caused by high energy and feedstock prices, it is important for the UK's chemical sector to adapt in order to move forward. One way of avoiding these impacts, is through the use of renewable energy in place of fossil fuels, and the use of renewable biomass as carbon feedstocks. If the UK chemical industry was to transition to more widespread use of biogenic feedstocks over the use of oil and gas, a sizable amount of biomass would need to be supplied domestically or through imports. Key biogenic feedstocks available in the UK include: cereal crops (e.g., wheat, barley, oats, oil seed rape) & cereal crop residues; sugar beet & sugar beet pulp; forestry biomass & forestry residues, perennial ryegrass, macroalgae, and industry wastes/residues (e.g., paper waste, distillery wastes, and bread manufacturing waste).

In order to promote the development of a bio-based chemical industry in the UK, government support should be utilized in order to encourage the advancement of novel manufacturing processes and the production of new bio-based drop-in chemicals and new-to-market products. However, it is clear that further development is needed in this area to develop effective policies that will help to drive the bio-based chemical industry and the wider bio-based economy going forward.

NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products.

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ANNEX 2

Stakeholder Engagement

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Department for Energy Security & Net Zero

Frey

Stakeholder Engagement Final Report: The use of Biomass to produce Biochemicals and Biomaterials

This report should be read in conjunction with associated reports as part of project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

The Bioeconomy Consultants NNFCC

Perspective Economics

Imperial College London

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Appendix 19

Executive Summary

In December 2022 the Department for Energy Security and Net Zero (formally BEIS) commissioned a 12-month independent study to assess the economic and climate benefits to the UK of an increased use of bio-based chemicals and materials.

NNFCC, FREY Consulting, Perspective Economics and Imperial College London were awarded the tender in January 2023, and the study commenced in February 2023.

The study aims to produce quantitative estimates of carbon and economic benefits of various biomanufacturing technologies, to highlight areas in which biomass use in the chemicals sector can best contribute to growing innovation and the economy, while also helping meet the UK's Net Zero ambitions.

This report is based on the analysis of stakeholder engagement, via an online survey and online 1:1 interviews and highlights the UK's current status and potential future opportunities for the use of biomass to produce biochemicals and biomaterials.

Stakeholders consulted included large, medium and small businesses, government officials, academics and trade bodies. In total the study to date has engaged with 69 individual organisations. 50 organisations completed the survey, and 50 organisations were interviewed.

Key Highlights:

- ~50% of organisations stated that they have some form of Net Zero, Decarbonisation or Defossilisation Targets. Only 3 organisations had plans to become net negative.
- All of the organisations engaged, saw the need to distinguish between decarbonisation and defossilisation. Since one of the main building blocks of both biomass and chemicals is carbon, these cannot be decarbonised, but instead need to be defossilised.
- 31% of organisations stated that they had an idea of the carbon footprint of their products. However, the wide range of methodologies used to carry out Life Cycle Analysis (LCA) of products means making comparisons between organisations and products is difficult.
- General consensus that technologies are known but have not been sufficiently scaled up or proven for industry to invest in them. There is a need for investment into a range of platform 'off the shelf' proven technologies that industry can utilise.
- Stakeholders agreed that the production and widespread adoption of biobased chemicals face several barriers that can hinder their development and implementation. The largest barriers include commercial viability of biobased products, the policy and regulatory environment and feedstock availability.
- All stakeholders agreed that the UK does not manufacture significant volumes of chemicals and that the best route to achieving the highest uptake of biomass would therefore be through the provision of platform biochemicals, to be used as the building blocks of more speciality biochemicals.
- Appetite to switch to biobased chemicals and materials exists, but larger organisations have no immediate plans to make any changes.
- Many companies consider carrying out R&D in the UK but manufacturing abroad is ultimately the best option due to incentives.
- Stakeholders thought that a mix of biorefinery and dispersed manufacturing would be the most likely scenarios for the future, and that the UK needs to be flexible in how we approach this, as we don't have too many incumbent domestic chemical producers, so siting alongside/repurposing current facilities would be the most attractive proposition.

Based on all information gathered through stakeholder engagement, a long list of potential future scenarios for the use of biomass to produce biochemicals and materials has been produced, which has then been reduced to a shorter list based on the below criteria:

- **CREDIBLE/ACHIEVABLE** – the feedstock and production technologies are available (commercial/demonstration now for 2030 horizon, demonstration/pilot now for 2040 horizon and lab now for 2050 horizon).

- **MEANINGFUL** – production/demand would be at a scale sufficient to make a meaningful carbon savings impact.
- **PLAUSABLE/REALISTIC** – There is clear UK interest in the production or use of the chemical (Ideally a UK chemical company producing/using or looking to produce/use).

Following on from this, quantitative analysis of the 15 potential biochemicals and materials was undertaken and presented at a second validation workshop on November 7th 2023, where barriers to a transition to these were discussed, alongside how the transition could be accelerated.

1. Introduction

The chemicals industry currently produces a large amount of chemicals of great benefit to society. Tens of thousands of chemical intermediates and products are essential components of, for example, polymers, pharmaceuticals, agrochemicals, fragrances, textiles and paints. Life without the modern materials produced by this important sector, would be very different from it is now and the overall quality of life would be greatly diminished.

The chemicals sector consumes about 14% of global oil production and 8% of gas, with virgin fossil carbon feedstocks accounting for 88% of inputs. 60% of the inputted carbon remains in the products, as embedded carbon. With over 96% of all products having some form of chemical in them, the role of defossilising the chemicals industry could have a huge impact on reducing the impact of our current reliance on fossil resources, and significantly lower new virgin fossil resource associated greenhouse gas emissions from entering the atmosphere.

It is generally accepted that there are three main non-virgin-fossil resources available for the manufacture of chemicals, biomass, CO_2 and recycled carbon. This study focuses solely on the roll of biomass as a feedstock.

In December 2022 the Department for Energy Security and Net Zero (formally BEIS) commissioned a 12-month independent study to assess the economic and climate benefits to the UK of an increased use of bio-based chemicals and materials.

NNFCC, FREY Consulting, Perspective Economics and Imperial College London were awarded the tender in January 2023, and the study commenced in February 2023.

The study aims to produce quantitative estimates of carbon and economic benefits of various biomanufacturing technologies, to highlight areas in which biomass use in the chemicals sector can best contribute to growing innovation and the economy, while also helping meet the UK's Net Zero ambitions.

The study aims to answer 3 key questions:

1. Which bio-based chemicals offer the largest potential for GHG emission savings relative to the fossil incumbents, this maybe a like for like replacement or an alternative product performing the same function
2. Formulate an understanding on how the UK's biomass resource can be sustainably (effectively and efficiently) processed to bio-based chemicals is required
3. What economic benefits could result from the increased production of bio-based chemicals including the value add over bioenergy application and the opportunity for the UK to develop a competitive advantage in export markets.

To answer these questions the study has 3 main components, which interface as shown in the table below:

1. Literature Review: On existing and nascent technologies for producing bio-based chemicals and materials, to gain an in-depth understanding of the current status in the UK
2. 2. Original Research: Industry and academic stakeholders will be engaged to elicit expert opinion on the UK's current status, opportunities and challenges, and future scenarios
3. 3. Quantitative Analysis: To estimate the potential economic and environmental impacts of bio-based chemicals and materials will require a quantitative methodology to consider several metrics.

	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
Literature review										
Stakeholder engagement: Survey and 1:1 interviews										
Stakeholder engagement: Validation workshop 1										
Economic Analysis										
Environmental Analysis										
Stakeholder engagement: Validation workshop 1										

This report is based on the analysis of stakeholder engagement activities, via an online survey, online 1:1 interviews, and two workshops, and highlights the UK's current status and potential future opportunities for the use of biomass to produce biochemicals and biomaterials.

2. Stakeholder Engagement

2.1 Engagement activities

Stakeholders were engaged via several activities throughout the study, as shown in the table above:

- Online Survey - https://www.surveymonkey.co.uk/r/5QF5F85
- 1:1 Interviews – held online between February and May 2023
- Validation workshop 1: June 26th 2023, where the top 15 biochemicals were presented to stakeholders
- Validation workshop 2: November 7th 2023, where the results of stakeholder analysis, literature review and quantitative analysis were presented to key stakeholders for validation.

2.1 Study Engagement

Stakeholders consulted during the study included large, medium and small businesses, government officials, academics, banks and trade bodies. In total the study has engaged with 69 individual organisations. 50 organisations completed the survey, and 50 organisations were interviewed, covering TRLs 1 to 9.

Organisations were from a variety of sectors including speciality chemicals, plastics, fibres, chemicals, biotechnology, consumer products, commodity chemicals, paper and coatings, biobased chemicals and materials, composites, agrochemicals, bioplastics, agriculture, circular economy and pharmaceuticals (See Appendix).

1.2 Information Collected

Information gathered through the survey and interviews included:

- Company information
- Company Net Zero, Decarbonisation, Defossilisation targets
- Chemicals / biobased chemicals produced today and volumes
- Biobased chemicals that are imported
- Biobased chemicals that are important for the future
- Feedstocks used
- Carbon footprints of products
- Current technologies used
- Information on the state of technology and innovation to transition to biochemical production
- Appetite of industry to transition
- Barriers to transitioning to biochemicals and materials
- Economic information
- Potential future manufacturing scenarios

2. Current Status of UK chemicals and biochemicals industry

2.1 Net Zero, Decarbonisation and Defossilisation Targets

~50% of organisations stated that they have some form of Net Zero, Decarbonisation or Defossilisation Targets. However, only 3 organisations had plans to become net negative.

All of the organisations engaged, saw the need to distinguish between decarbonisation and defossilisation. Since one of the main building blocks of chemicals is carbon, they cannot be decarbonised, but instead need to be defossilised.

> We can decarbonise the energy sector, but not the chemicals sector.
> What we can do is defossilise the chemicals sector.
>
> …By the way, the human body contains 23 wt-% carbon. Just imagine what would happen, if we decarbonised everything"

While the defossilisation and decarbonisation of energy systems is well understood, the decoupling of fossil resources from the chemical industry has often been overlooked, due to the abundance of cheap fossil feedstocks, which are used to produce plastics and fibres, fertilisers, pesticides, personal care, and consumer products, among other ubiquitous chemicals. The key challenge with defossilisation of chemical industry is the requirement for carbon-based feedstocks. Chemical demand is also expected to grow rapidly in the coming decades, and, without major disruption to feedstocks, could become the largest driver in oil consumption.

Net Zero: a target of completely negating the amount of greenhouse gases produced by human activity, to be achieved by reducing emissions and implementing methods of absorbing carbon dioxide from the atmosphere.

Decarbonisation: to reduce the amount of gaseous carbon compounds released in or as a result of an environment or process.

Defossilisation: to reduce the amount of virgin fossil resource utilised in a product or process.

There was also a clear understanding from stakeholders that simply becoming Net Zero would not be enough, and that further action would be required for some processes to become Net Negative to ensure that atmospheric carbon dioxide levels do not continue to rise.

Most stakeholders agreed that the chemicals industry should address scope 1, 2 and 3 emissions, and not rely on off-setting of emissions.

Net Zero, decarbonisation and defossilisation targets varied widely amongst stakeholders, and included:

- Organisation signed up to Science Based Targets initiative (SBTi's) and have scope 1, 2 and 3 targets. 20% reduction in CO_2 as of 2020 baseline, by 2030. Scope 3 30% reduction, likely to be through recycling.
- Net Zero by 2028.
- Net zero by 2030.
- 25% GHG emissions reduction by 2030. Net Zero by 2050. Biomaterials form part of the strategy.
- We intend to measure of Carbon footprint this year and confidently expect it to be less than zero.
- We do not have an overall net zero date, but biobased chemicals are part of our solution.
- By 2030, we will have achieved our SBTi's, in line with limiting global warming to 1.5°C. Thereafter, by 2050 we will be a net zero organization. Yes, biomaterials form part of the strategy.
- The use of biobased chemicals is something we are looking at.
- Internal commitments, but not publicly published at this time.
- Currently in the measuring and monitoring phase. We do have some reduction targets, but they are internal. We would use biobased chemicals if they were available.
- Net Zero scope 1 and 2 by end of 2024 and true carbon negative capturing carbon by 2030.
- Net zero by 2050. 33% reduction in emissions by 2030. Renewable feedstocks are one of several levers we are evaluating and implementing.

- Net zero for scope 1 & 2 operated asset greenhouse gas (GHG) emissions by 2050. Adoption of bio-based and bio derived materials is a key element.
- Net Zero by 2035. Intend on being carbon negative 250million tonnes.
- Net zero by 2040 and in April 2021 we signed up to the UN Global Compact's Business Ambition for 1.5°C.
- Net zero by 2040, where materials mix (mass balance) is the core of our decarbonisation strategy.
- Net negative for 2025.
- Net zero carbon by 2030. Biobased chemicals are a part of the strategy to achieve this goal.
- Net zero by 2039. Yes, adoption of biobased chemicals is a big part of the strategy, along with other renewable sources of carbon for chemicals manufacture - recycling and Carbon Capture and Utilisation.
- Scope 1 & 2 net zero by 2030.
- We have established some net zero goals and KPI's for the business. Green chemicals and contribution to revenue will become a KPI for us to help deliver our Sustainability agenda.
- Net Zero by 2028. There is a full biobased program in place involving third party research and scale up partners.
- Net Zero by 2050 for Scope 1 and 2. No Scope 3 targets. Will achieve through reducing energy consumption. Focus on Carbon Capture and Storage to decarbonise and blue hydrogen.

2.2 Carbon Footprint and Life Cycle Analysis

31% of organisations stated that they had an idea of the carbon footprint of their products. However, the wide range of methodologies used to carry out Life Cycle Analysis (LCA) of products means making comparisons between organisations and products is very difficult. The three types of LCA's used are:

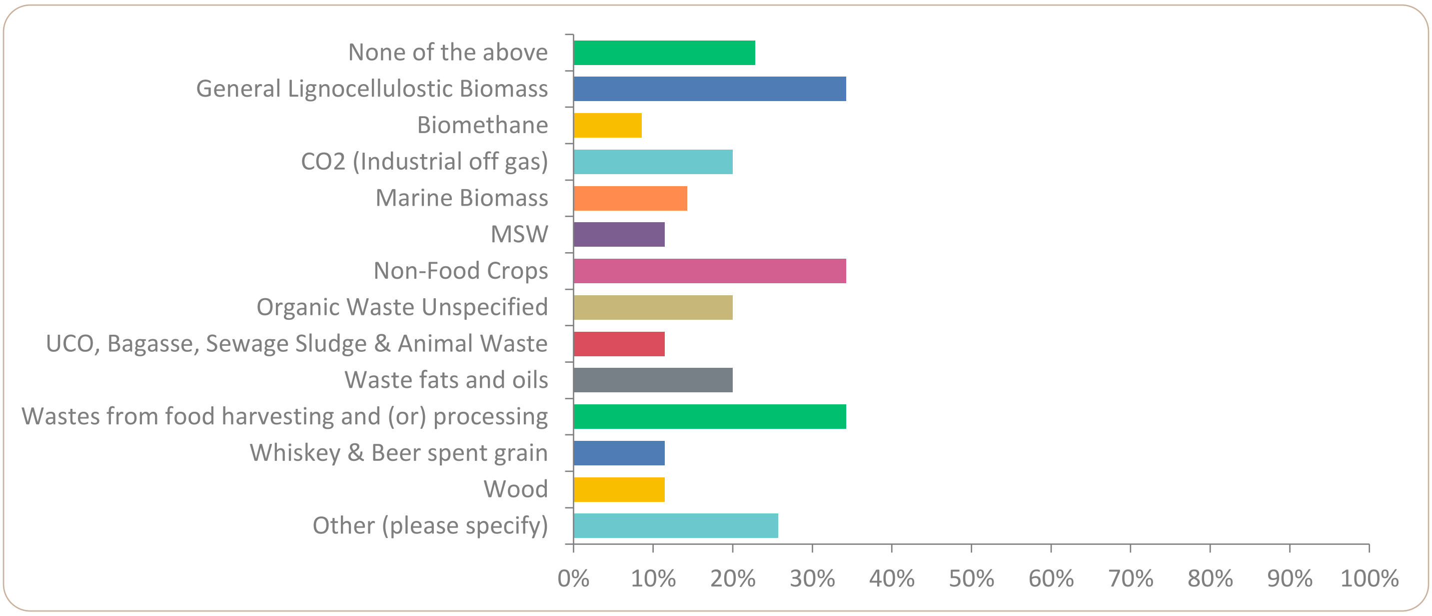
- Cradle-to-gate: Cradle-to-gate only assesses a product's footprint until it leaves the factory gates before it is transported to the consumer.
- Cradle-to-grave: Cradle-to-grave shows a full footprint from start of life to end of life.
- Cradle-to-cradle: Is a variation of cradle-to-grave but exchanges the waste stage with a recycling/upcycling process that makes it reusable for another product – essentially "closing the loop".

The importance of full LCA was provided by Corteva Agrisciences, who noted that they would accept an increase in CO_2 emissions in the manufacture of their biological products, if it led to an overall reduction in the environmental impact of their products, e.g., 1 gram of biobased pesticide required, compared to 1kg of fossil fuel derived. To see this benefit, a full cradle-to-cradle analysis is needed.

It was agreed by most stakeholders that a standardised LCA for biobased materials was required. It was also agreed that in general we are lacking a workforce with the skills to carry out accurate LCAs.

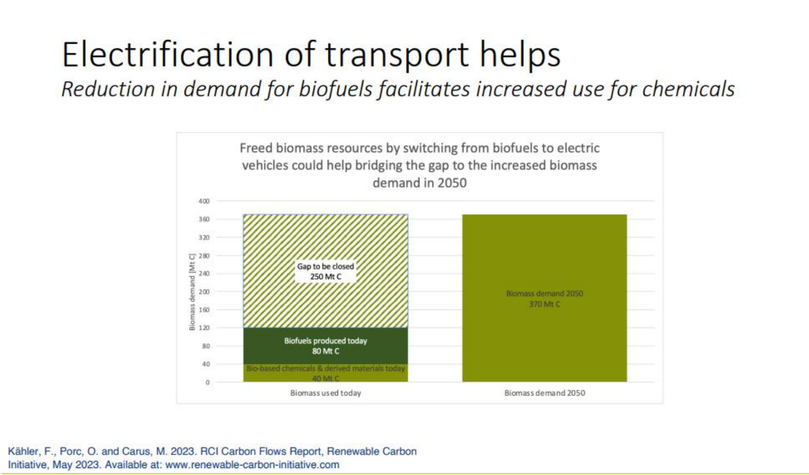
2.3 Feedstocks

Stakeholders were asked which biomass feedstocks they currently use or were planning to use to manufacture any bio-based chemicals or materials. General lignocellulosic biomass, non-food crops and waste from food harvesting are the most used feedstocks. 'Other' feedstocks included pulp, starch, sugar, vegetable oils, Feed grade grains, Dextrose from corn and a range of agricultural protein hydrolysates, hydrogen, glucose, waste cooking oils.



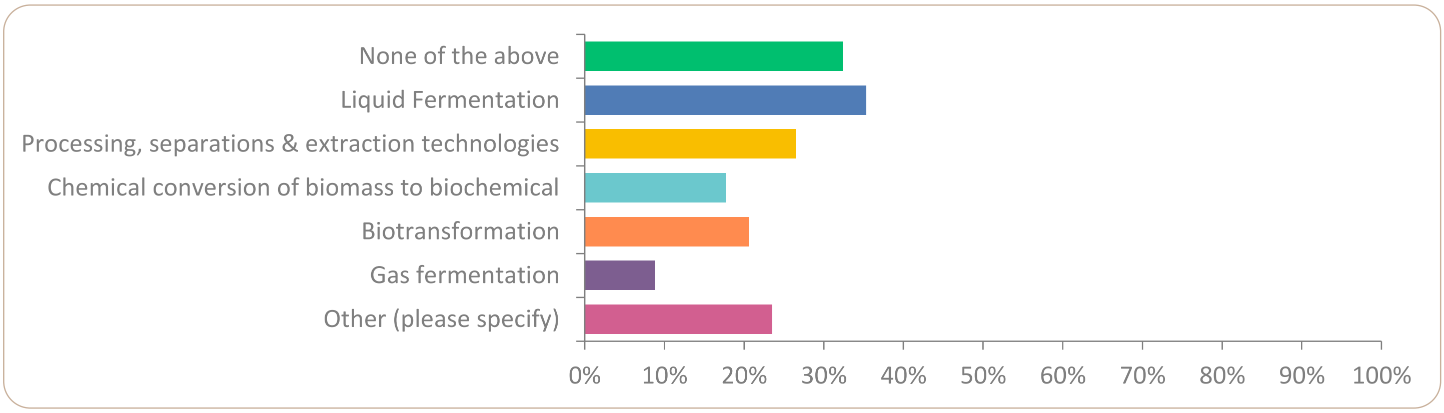
The demand for carbon from biomass for chemicals is estimated to be 370 million tonnes in 2050. Several studies have tried to estimate how much biomass will be available in 2050. Mid-range global estimates of biomass available in 2050 range from 3-6bn tonnes carbon, but there is a huge variability in literature (3-86bn tonnes). Estimates are 'what if' scenarios rather than predictions, and key variables include:

- Rate of crop yield improvement
- Extent to which productive land is used for biomass crop cultivation
- Extent of intensive farming
- Size of future population
- Changes in diet



2.4 Technologies

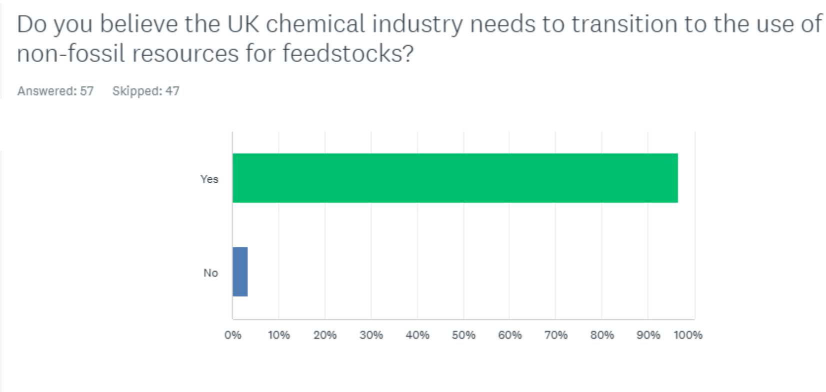
Stakeholders were asked what technology(ies) they currently used to produce any bio-based chemicals or materials. Liquid fermentation was the technology most widely used. 'Other' technologies included polymerisation, viscose process, aqueous chemical processing, solid state fermentation, enzymatic conversion, hydrolysis, and reactive extrusion.



Stakeholders we also asked what they thought the current state of development and innovation was regarding bio-based production technologies. There was an overwhelmingly unanimous response that the technologies were known and proven at lab-scale. However, for industry to adopt new technologies, the Technology Readiness Level (TRL) needs to be at least 7 or 8. There is a need for investment into a range of platform 'off the shelf' proven technologies that industry can utilise.

2.5 Appetite to Transition to Biobased Chemicals and Materials

Stakeholders were asked if they thought that the chemicals industry needs to transition to the use of non-virgin-fossil resources for feedstocks. 97% agree that a transition is needed.



However, when stakeholders were asked to describe the appetite among UK chemicals and materials producers to pursue biomass feedstock alternatives (not carbon dioxide or recycled carbon as a feedstock) responses varied widely:

- Several large-scale chemical assets exist in the UK at present, and larger organisations stated that the pathway to Net Zero with existing infrastructure is challenging. Large organisations overall did not think that the appetite to change was present yet.
- Micro, smaller, and medium organisations mostly saw a large appetite for change from consumers and believed that the sector was beginning to realise the need to transition away from a reliance on virgin-fossil resource as a feedstock.
- Stakeholders noted that some customers were asking for product carbon footprints/ Lifecycle Analyses but were unwilling to pay extra for ones with lower carbon footprints at this time.
- There was a consensus that some end consumers would pay more for more sustainable products.

- The two main factors affecting appetite for to transition, were market demand, and cost of manufacture.

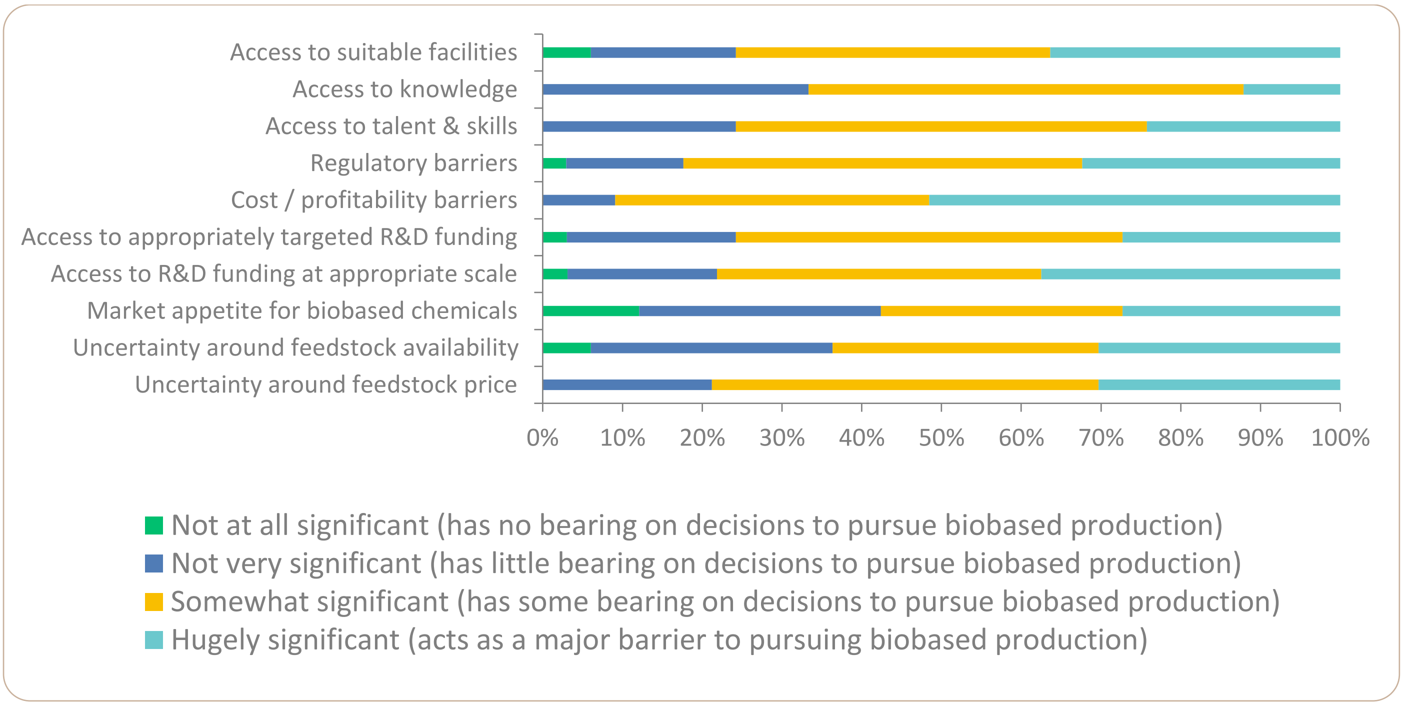
Market drivers for a transition to biomass feedstocks suggested by stakeholders included:

- The political desire to show green leadership – translates into pressure on businesses
- A growing sense of urgency in the industry. Partly driven by long lead times for new products, processes and manufacturing facilities
- Growing pressure for carbon accounting and traceability throughout the supply chain
- Risks to licence to operate
- Risks to access to investment, finance and insurance for potentially unsustainable activities
- The uncertain future of the oil and gas industry – new solutions for consumer products will take time to develop. Could events overtake us?
- Emerging models for carbon taxation

2.6 Barriers to Transitioning

Stakeholders were asked what the most significant barriers are facing their organisations, and/or the sectors, expansion of or switching to biobased chemical production.

Stakeholders agreed that the production and widespread adoption of biobased chemicals face several barriers that can hinder their development and implementation.



Some of the significant barriers include:

Cost/Profitability: The greatest barrier to transitioning is perceived to be economics. Biobased chemicals often face cost competitiveness challenges when compared to their fossil-based counterparts. High capital investment costs, limited economies of scale, and the dependency on fluctuating feedstock prices can make biobased chemical production economically unviable. Achieving cost parity or cost advantage is crucial for their commercialisation and widespread adoption. Since businesses work on short (1-3 year) business plans, where profit is the main KPI, reduced profits are not usually accepted by shareholders.

Feedstock Availability and Price: Biobased chemicals are derived from renewable resources such as plants, agricultural waste, or algae. The availability and consistent supply of these feedstocks can be a challenge. Factors such as land availability, climate variability, and competing uses (e.g., food production) can limit the availability of feedstocks and impact the scalability of biobased chemical production. Access to consistent specification feedstocks, at the required volume, required specification, and consistent cost, alongside understanding future feedstock availability was also highlighted as a key barrier.

All stakeholders highlighted the issue of ensuring that the uptake of using a certain biomass did not replace its usage elsewhere, leading to overall less sustainable practices. One example described was the use of animal fat to produce jet fuel, where airlines are under pressure to reduce their carbon emissions, which mainly come from burning fossil-based kerosene in aircraft engines. Demand for fuel made from biomass or derived from animal by-products is expected to triple by 2030. But experts fear scarcity will force other industries to use more palm oil – potentially a significant generator of carbon emissions. A second example was distillery by-products, traditionally used as an animal feed, being diverted to produce biobased chemicals, leading to farmers importing soy from Brazil, which generates significantly more carbon emissions.

Technological Challenges: The conversion of biomass into biobased chemicals often involves complex and resource-intensive processes. Developing efficient and cost-effective technologies for biomass pretreatment, enzymatic hydrolysis, fermentation, and chemical conversion poses technical challenges. Optimization of these processes, as well as improving the yield and selectivity of target chemicals, requires ongoing research and development efforts. As mentioned above, there was an overwhelmingly unanimous response that the technologies required to transition to biobased chemicals are not at high enough TRLs for industry to adopt them.

Infrastructure, Energy and Logistics: The existing infrastructure for the production, storage, and transportation of chemicals is typically designed for fossil-based chemicals. Establishing a dedicated infrastructure for biobased chemical production, including feedstock collection, processing facilities, and distribution networks, requires significant investment. In addition, the significant investment in existing assets, which utilise fossil resources, means that organisations want to utilise these as much as possible, before making any new investments. The conversion of biomass into biobased chemicals often involves resource-intensive processes, and so access to cheap renewable and low-carbon energy was highlighted as being essential for the transition away from fossil resources.

Access to Scale-up Facilities: Many stakeholders cited the need for UK pilot and demonstration facilities to be available to help scale up technologies and processes, alongside the need for subsidised access to such facilities for SMEs. Many organisations are currently having to take their processes to Europe to carry out scale -up.

Access to Finance: The need for long-term access to finance was seen as an issue by most stakeholders, spanning the full TRL. Several stakeholders noted that the lack of longevity of funding meant that lots of great projects get to TRL 3 or 4 but never any further. It was also noted that for SMEs that innovate UK funding was inaccessible for some due to the need for them to fund 30% of costs themselves and have funds upfront before claiming back. In terms of investment, stakeholders felt that the UK does not support start-ups in the biochemicals sector, and that most investment is from abroad. For example, Holiferm has secured most of its investment from the US and EU. One stakeholder sited that Sanofi, one of the largest investors in the biochemicals space, has not made an investment in UK since Brexit.

Policy and Regulation: Policy frameworks and regulations play a crucial role in shaping the market for biobased chemicals. Inconsistent or unclear regulations, lack of supportive policies, and limited financial incentives were seen to hinder investment and impede market growth. Stakeholders believe that well-defined policies that encourage the use of biobased chemicals, provide incentives, and address potential environmental and social impacts are essential in creating a favourable environment for their adoption. One particular issue that was highlighted by stakeholders was that new products manufactured from biomass need to have the same, or better performance than their fossil resource counterparts, which requires requalification of specification – which is extremely costly. Many stakeholders also noted that fees to register a new chemical product with REACH, could span into the millions, making the biobased products development unviable.

Market Acceptance: Stakeholders notes that biobased chemicals often face challenges in gaining market acceptance due to various factors, including cost differences, limited awareness among consumers, potential performance gaps compared to conventional chemicals, and resistance from established industries. Stakeholders felt that demonstrating the performance, safety, and sustainability benefits of biobased chemicals and educating consumers and industries about their advantages is crucial for market acceptance and demand creation.

Access to Expertise: SMEs in particular noted that gaining access to academic expertise was difficult, and finding out where expertise are available was hard – not knowing which researchers or institutions specialize in the areas relevant to their needs. Industry also had concerns about intellectual property (IP) and ownership when collaborating with academia.

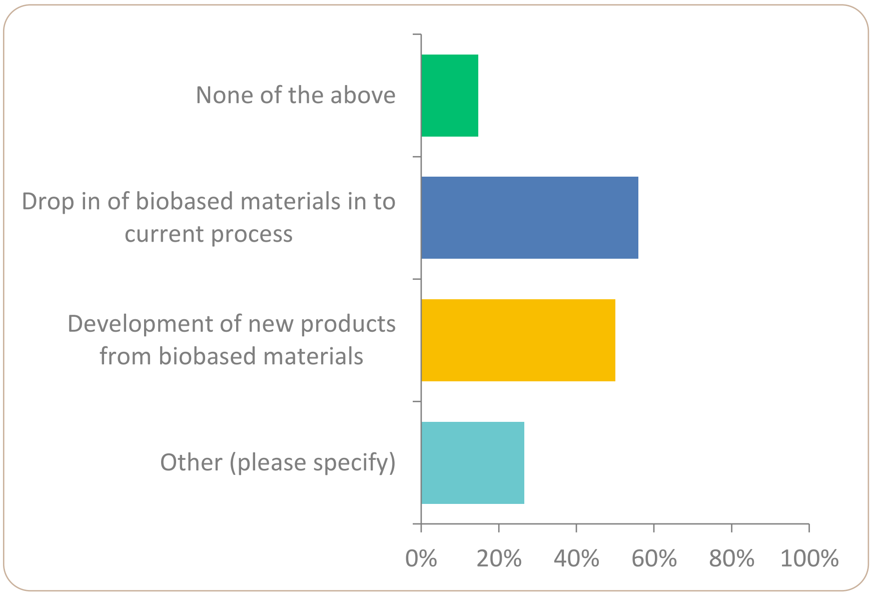
Skills Shortages: Several stakeholders noted the UK has a skills gap in biochemical engineers who could translate chemical processes into biobased ones. There is a need for individuals with strong technical skills in biochemical engineering processes, including knowledge of bioreactor design and operation, fermentation, downstream processing, and process optimization. The application of advanced technologies, such as computational modelling and data analysis, also requires specialized expertise. A skills gap around LCA was also noted. For example, Holiferm cited that they have struggled to find the skilled workforce they need and are having to spend increasing amounts on visa fees to bring in talent from abroad.

Social Impact: There was a perception amongst stakeholders that the public did not consider climate change as an immediate threat, and that the UK was going to be able to mitigate any effects. Stakeholder felt that addressing these barriers requires a multi-faceted approach involving collaboration among industry, academia, policymakers, and research institutions. Investments into public awareness campaigns are vital for overcoming these barriers and promoting the widespread adoption of biobased chemicals.

Brexit: many stakeholders cited Brexit and not being able to access EU funding for a timeframe has led to a drop in UK biochemicals sector growth.

3. Future Opportunities

3.1 Transition and Production of biobased chemicals and materials



When asked about the potential to transition to biobased chemicals, both the drop in of biobased materials and development of new materials were cited almost equally as routes that the sector would consider. 'Other' specified the use of both.

Smaller organisations and those developing new products and processes were more aligned to working with available feedstocks and technologies and building the required infrastructure to fit.

Larger organisations and those with significant existing assets, were keen to utilise such assets as much as possible, and primarily transition to the drop-in use of bio-based materials. This would be via the mass balance approach[92].

The concept of mass balance is based on the principle that mass inputs to a system are equivalent to the outputs. Therefore, mass balance in this context allows for the allocation of renewable content to specific products in order for manufacturers to benefit from the ability to make a meaningful product claim. A link is made between product and raw material, which highlights the amount of fossil feedstock that has been displaced, even if physically the product contains a lower renewable content.

For drop-in biochemcials, producers of renewable biomass can supply the chemical industry who can then benefit from their renewable supply chains. Neste for example, produce 'MY Renewable Naphtha' utilising vegetable oils and waste fats and UPM's 'BioVerno naphtha' uses crude tall oil, a residue of pulp making process. These feedstocks are

[92] Mass Balance.pdf (nnfcc.co.uk)

finding increasing use, for example Borealis, a polyolefin manufacturer, is to employ Neste's naphtha for mass balanced renewable polypropylene production.

BASF commented that they could process 100% of their naphtha (50% of current feedstock) as bio-naphtha as of today if the biomass feedstock was available. In this mass balance approach, renewable resources such as bio-naphtha or biomethane derived from organic waste, crops or vegetable oils are used as feedstock in the very first steps of chemical production. The bio-based feedstock amount is then allocated to specific products sold by means of the certified method. However, it is important to note that the amount of biomass that would be required would most likely never be available.

Alpek Polyesters commented that they could switch to using 100% BioMEG (30% of current feedstock) in their process as of today if the BioMEG was available in the quantities required and at an economically viable cost. Those organisations with exiting assets stated they would invest in modifying exiting capital infrastructure to be able to use biomass if the opportunity was commercially viable.

All stakeholders agreed that since the UK does not manufacture significant volumes of chemicals that the best route to achieving the highest uptake of biomass would therefore be through the provision of platform biochemicals, to be used as the building blocks for more speciality biochemicals. However, the UK does not produce significant amounts of platform chemicals, and therefore investment into domestic biorefineries would be essential.

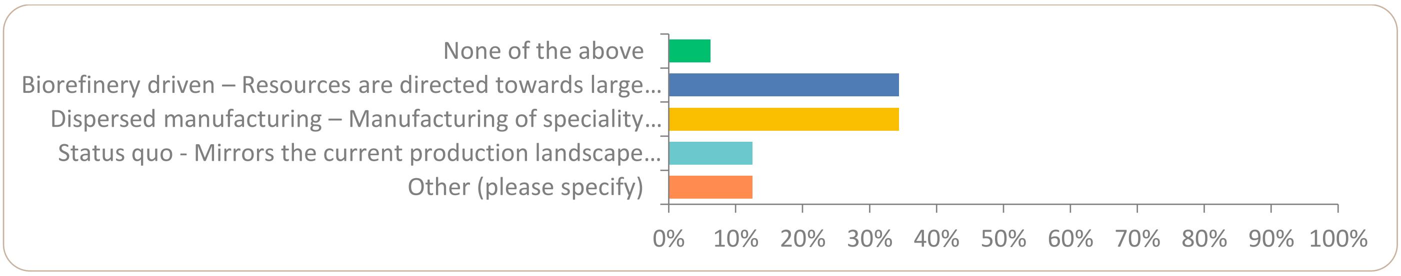
Stakeholders were asked which of three production scenarios they thought would be best for the UK to adopt when thinking about achieving the highest CO_2 savings through biomass usage:

(1) Biorefinery driven - renewable carbon as a feedstock is directed towards large scale centralised facilities

(2) Dispersed manufacturing – renewable carbon as a feedstock is directed towards manufacturing of speciality chemicals at a meaningful scale to impact on GHG emissions

(3) Status quo - Mirrors the current production landscape with production transitioning to the use of renewable carbon as a feedstock (biomass, CO_2 and chemical recycling).

Stakeholders thought that a mix of biorefinery and dispersed manufacturing would be the most likely scenarios for the future, and that the UK needs to be flexible in how we approach this, as we don't have many incumbent domestic chemical producers, so siting alongside/repurposing current facilities would be the most attractive proposition.



Three stakeholders mentioned the need for the UK to Horizon Scan in terms of what the chemistry set of the future looks like - is it the same as today? They suggested that the sector needs to define what the products of the future are, and then begin to determine how we can make these from biomass.

3.2 Potential Future Scenarios

Based on all information gathered through the literature review and stakeholder engagement, a long list of 70 potential biochemicals and materials was produced (see Appendix, Table 2). The potential future scenarios were then grouped into the 3 production scenarios.

The long list of 70 potential biochemicals and materials was then reduced to the 15 most likely future scenarios (Table 1) based on the below criteria:

- **CREDIBLE/ACHIEVABLE** – the feedstock and production technologies are available (commercial/demonstration now for 2030 horizon, demonstration/pilot now for 2040 horizon and lab now for 2050 horizon).
- **MEANINGFUL** – production/demand would be at a scale sufficient to make a meaningful carbon savings impact.
- **PLAUSABLE/REALISTIC** – There is clear UK interest in the production or use of the chemical (Ideally a UK chemical company producing/using or looking to produce/use).

Infrastructure, demand and integration was also incorporated by considering where biobased chemical production might fit with current activity and infrastructure, reviewing chemical import data to understand downstream industry needs, and incorporating stakeholder insights (Figure 2).

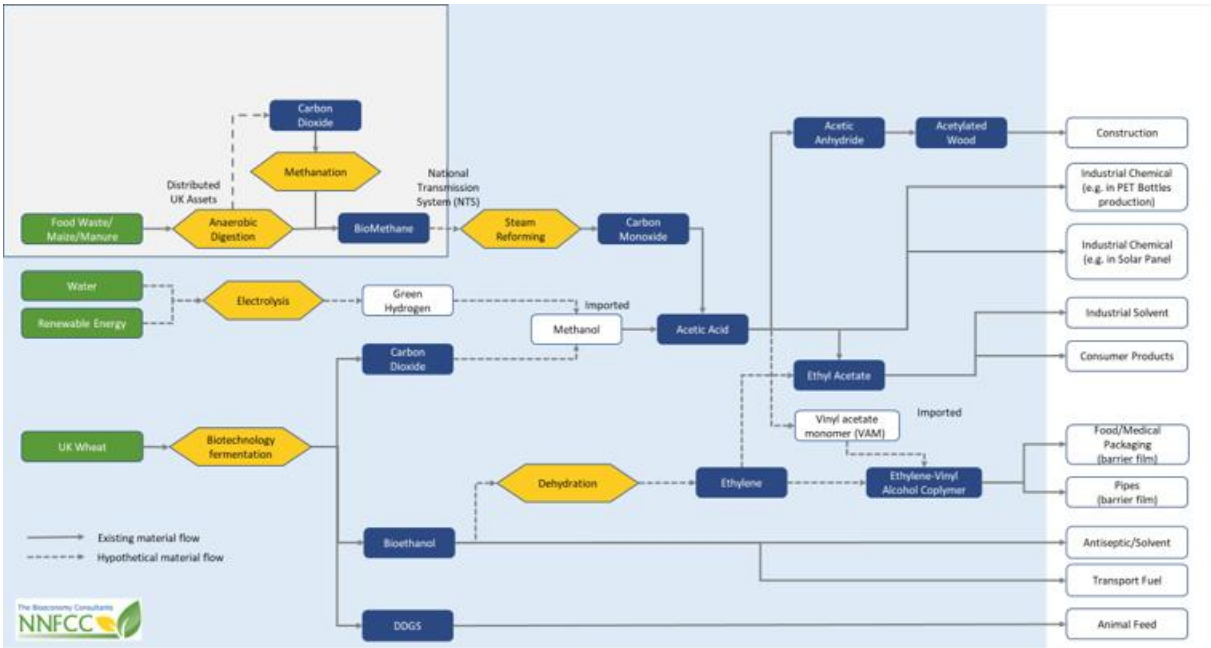


Figure 2. Infrastructure, demand and integration for transition to biobased chemicals and materials

Table 1. Future scenarios for biobased chemical and materials, and potential UK sponsors

	Manufacturing option		
	Biorefinery	**Distributed Manufacturing**	**Business as usual***
Potential biobased chemical/material	**LACTIC ACID** via fermentation for solvent and polymer production	**BUTANOL, ACETONE AND ETHANOL** via ABE fermentation for solvent applications	**BIOBASED PROPANE** from SAF production as feedstock for crackers (ethylene, propylene etc)
	MONOETHYLENE GLYCOL via sugar hydrolysis for polymer and surfactant production	**BIOSURFACTANT** Via fermentation for solvent applications	**BIOBASED NAPHTHA** from SAF production as feedstock for crackers (ethylene, propylene etc)
	ETHYL ACETATE via ethanol for solvent applications	**FURANDICARBOXYLIC ACID (AND HMF)** via sugar chemistry for surfactant and polymer production	**BIOBASED METHANE (BIOMETHANE)** as feedstock for acetic acid, acetic anhydride and ethyl acetate production.
	ETHYLENE via ethanol for polymer production	**BUTANEDIOL** via fermentation for polymer production	
	METHYL METHACRYLATE via fermentation for polymer production	**SUCCINIC ACID** via fermentation for polymer production	
	METHANOL from green hydrogen and CO2 off gas	**DIHYDROLEVOGLUCOSENONE** via sugar chemistry as a novel solvent	

*Most likely mass balance approach

These scenarios were presented at a workshop on Monday 26th June 2023, attended by over 65 stakeholders and validated as reasonable potential future scenarios.

4. Considerations for Accelerating the Transition to Biobased Chemicals

Following on from this, quantitative analysis of the 15 potential biochemicals and materials was undertaken and presented at a second validation workshop on November 7^{th} 2023, where barriers to a transition to these were discussed, alongside how the transition could be accelerated, which are highlighted below:

Strategy: All stakeholders supported the need for a clearer vision for an industrial Net Zero Pathway that is aligned across government departments, including Defra, DSIT, DEZNS, DBT. The strategy needs to back the use of renewable carbon sources and commit investment into scaling technologies. Such as strategy should also lay out incentives for using renewable carbon, where the most benefit is to be had – both environmentally and economically.

Many stakeholders pointed to, how Under the Inflation Reduction Act in the USA, the administration has established new targets for the American bioeconomy, through its new 'Bold Goals for U.S. Biotechnology and Biomanufacturing' strategy, with ambitious goals for their chemicals and materials sector. Engineering biology and biomanufacturing are core to all this work. Theme 2 of the strategy seeks alternative processes to produce chemicals and materials from renewable biomass and intermediate feedstocks by developing low-carbon-intensity product pathways and promoting a circular economy for materials. Achieving these goals will position the United States at the forefront of a vibrant global bioeconomy while producing net-zero or net-negative emissions, reducing use of and reliance on fossil fuels, and increasing use of recyclable-by-design chemicals and materials like bio-based products. Alongside this, they have set ambitious targets:

Theme 2: Chemicals and Materials
Goal 2.1: Develop Low-Carbon-Intensity Chemicals and Materials – In 5 years, produce >20 commercially viable bioproducts with >70% reduced lifecycle GHG emissions over current production practices.
Goal 2.2: Spur a Circular Economy for Materials – In 20 years, demonstrate and deploy cost-effective and sustainable routes to convert bio-based feedstocks into recyclable-by-design polymers that can displace >90% of today's plastics and other commercial polymers at scale.

Whilst the US's aspirational targets may seem difficult to achieve, the administration has put financial resources behind the policy to stimulate production of biochemicals.

Policy and Regulation: Stakeholders felt the government had a crucial role to play in promoting the adoption of bio-based chemicals through supportive policies and regulations. This includes providing incentives such as tax credits, grants, and subsidies for research and development, production, and use of bio-based chemicals.

- For example, in January 2017 France mandated use of compostable materials for single-use supermarket bags and food packaging, leading to growth in its biomaterials industry. Stakeholders felt the UK should investigate and implement similar policies designed to promote the bio-based chemicals listed in this report.
- Another example cited by many stakeholders was the policy around recycled plastics and tax incentives if plastics contain more than 30% recycled plastic by content. It was strongly felt that this should be rolled out to all materials containing more than 30% biomass, which would aid the transition to biobased via the mass balance approach.
- Regulatory incentives would create market pull for biobased chemicals and drop in equivalents. This, for example, has been successful in fuels (RTFO) and Sustainable Aviation Fuels.
- Stakeholders felt that lessons could be learnt from the US, where they have a bio-preferred scheme[93], that aims to assist in the development and expansion of markets for biobased products. The program was created by the 2002 Farm Bill (legislation) and expanded as part of the 2014 Farm Bill. For example, UK government could specify that the NHS must procure certain biobased materials (e.g., disposable gloves) by a certain time. This would drive market demand.
- In addition, stakeholders thought that the UK could mimic elements of the US Inflation Reduction Act[94].
- Stakeholders noted the need to be able to match and offer greater incentives provided by other countries if some other natural barriers (e.g., feedstock availability) are to be overcome.

93 FACT SHEET: Overview of USDA's BioPreferred Program | USDA
94 Inflation Reduction Act Guidebook | Clean Energy | The White House

- Stakeholders agreed that for biomass to be given an equal playing field to fossil carbon, that subsidies for oil and gas need to be stopped, or reduced, and/or subsidies for biomass feedstocks should be implemented.

The need for standardised carbon accounting was agreed by the majority of stakeholders, alongside a tax on fossil-based carbon extraction and emissions. It is suggested that such carbon taxes need to be applied from beginning of the supply chain, and at point of emissions, and that they should start off low, and then increase.

All stakeholders noted the need to simplify REACH registration for chemicals made from biobased feedstocks, and to subsidise the cost. Stakeholders noted also that the process for getting permits for use of waste streams needs o be simplified to enable biomass to be used at scale for biochemicals. Stakeholders also felt green trade deals would benefit the biobased industry.

Access to feedstocks: Stakeholders raised the need of increasing availability of biobased feedstocks at scale and at a competitive price. The importance of creating appropriate systems for biowaste collection and valorisation was also highlighted. Concerns raised over feedstock availability included:

- There may not be enough biomass for all potential applications
- Competition for biomass feedstock from other users, e.g., SAF
- Ideally, biomass should be available close to the existing processing assets – what is available may be in the wrong place

Funding and Investment: Consistent long-term funding for research and development in bio-based chemicals, including funding for academic institutions, research organizations, and private companies is required. This financial support would help accelerate technological advancements, scale-up production, and reduce costs, making bio-based chemicals more competitive with their conventional counterparts. Research funding focussed on developing cost-effective ways to produce biobased chemicals and their derivativities, and on ways to scale them up to commercial products, will underpin viable commercial models. Stakeholders also noted that UK companies need technology testing and scale up services, and open access piloting and demonstration facilities. Technology advances in feedstock pretreatment and the supply of low-cost renewable sugars will also be an important enabler for the development of bio-based chemicals.

The Horizon 2020 programme and the Circular Bio-based Europe Joint Undertaking (CBE JU) programme was mentioned by several stakeholders as an example the UK could replicate. CBE JU is a €2bn partnership between the European Union and the Bio-based Industries Consortium (BIC) that funds projects advancing competitive circular bio-based industries in Europe. It funds projects across the full TRL scale.

Infrastructure Development: Stakeholders highlighted the need for investment into the development of infrastructure to support the production, storage, and distribution of bio-based chemicals. This includes building or retrofitting facilities for bio-based chemical manufacturing, establishing storage and transportation networks, and promoting the development of sustainable feedstock supply chains. Help is required to finance infrastructure for demo plants and finance for equipment. The (affordable) availability of pilot-scale facilities to de-risk scale-up and commercialisation, was noted by all stakeholders, to enable innovation activities to remain in the UK.

Market Demand and Awareness: Stakeholders felt the Government could help create market demand for bio-based chemicals by raising awareness among consumers, industries, and procurement agencies about the benefits of these products. Promoting labelling and certification schemes, consumer education campaigns, and sustainable public procurement policies could stimulate demand and encourage industries to transition to bio-based chemicals. Communication and the language used to describe biobased products also needs to be assessed and simplified to ensure consumer are not led astray over product claims.

Collaboration and Partnerships: Stakeholders believe the Government can foster collaboration between academia, industry, and other stakeholders to drive innovation and knowledge sharing in the bio-based chemicals sector. Public-private partnerships, technology transfer programs, and collaborative research initiatives could accelerate the development and adoption of bio-based chemicals.

A few stakeholders noted the success of the Vaccines Taskforce during the pandemic and thought the Government should create a Climate Task Force to drive forward the UK's response to global warming.

International Cooperation: Since climate change is a global issue, stakeholders felt that the Government should be collaborating at the international level on joined up research projects, harmonising standards, sharing best practices, and facilitating trade in bio-based chemicals. This would help create a level playing field, promote market access, and encourage global adoption of bio-based chemicals.

Sustainability and Life Cycle Assessments: All stakeholders noted that the Government should consider the environmental and social sustainability of bio-based chemicals throughout their life cycle. Robust sustainability standards and life cycle assessments are needed to ensure that bio-based chemicals deliver significant environmental benefits compared to conventional fossil-based alternatives. Considering the impact of embedded carbon in chemicals and end of life release is critical in ensuring circularity through biomass use. The understanding and acceptance of mass balance as a mechanism to enable transition from fossil based to biobased at scale, was also noted. For LCAs stakeholders agree that wider impacts beyond climate change are important to consider, such as resource depletion, acidification, eutrophication, eco- and human toxicity.

Key enablers for a transition to biomass as a feedstock for biochemicals: Stakeholders were asked what key enablers were required to accelerate a transition to biochemical production, to make products that were commercially and technologically viable, which included:

- Provision of cost effective renewable low-carbon energy, through a greener, renewable grid
- Advanced Machine Learning and AI tools to increase efficiency and reduce lead times
- Production of domestic low-cost cellulosic sugars
- Better CCU technology – PSA, MOS for carbon capture and proven direct air capture
- Improvements in 1st & 2nd gen sugars from biomass – especially managing the transition
- Faster, cheaper, scalable biotech. Including:
    - Easier retrofit
    - Scalable and versatile biotransformation's
    - Better engineering of bioprocesses
    - Improved extraction and dewatering processes
- Technology that can be used for distributed production and supply
- Better deoxygenation technologies and economic uses for released O_2.
- A UK waste regime, emissions trading schemes and energy policy, that support using waste or biomass for chemicals
- Shift the tax burden between sourcing and emissions to level the playing field and distribute the costs across the supply chain and consumer.
- Atom and energy efficiency to drive policy. Prioritise using renewable carbon in applications with the best value for energy expended and recognise the atom efficiency when selecting innovations for support.

5. A potential transition for the use of biomass as a feedstock for the chemicals industry

Using stakeholder engagement feedback, outcomes of the literature review and quantitative analysis, a potential transition pathway to the use of biomass for biochemicals is proposed below.

As of today, the global chemicals industry relies on fossil resources for 88% of its feedstock and contributes to ~10% of global annual greenhouse gases.

The bio-*based* chemicals industry currently generates an estimated £1.6bn in revenue.

Intervention		By 2040	By 2050
Manufacturing capability	Distributed	Distributed manufacturing capacity of 180,000 tonnes	Distributed manufacturing capacity of 500,000 tonnes
	Biorefinery	6 biorefineries type facilities with a capacity of 420,000 tonnes	6 biorefineries type facilities with a capacity of 1,000,000 tonnes
	Business as usual	200,000 tonnes of bio-attributed chemical capacity	580,000 tonnes of bio-attributed chemical capacity
Transformations required		UK government develop a unified cross-departmental biomass utilisation hierarchy and associated joined up policies and regulatory environment that ensures sustainable sourced biomass and biowastes are prioritised for high value materials and products, to derive the maximum value from our bio-resources	
Key enablers		Increase availability of sustainable biomass, low cost accessible renewable energy; access to green hydrogen; transparent data sharing	

Bio-based chemical	Volume produced (tonnes)	CO_2e savings	Economic value £	Volume produced (tonnes)	CO_2e savings (tonnes CO_2eq/tonne)	Economic value £
Lactic acid	50,000	122,00	76,945,000	100,000	244,000	153,890,000
Monoethylene glycol	50,000	108,000	26,745,000	200,000	430,000	106,982,000
Ethyl acetate	100,000	250,000	63,760,000	300,000	750,000	191,280,000
Ethylene	200,000	582,000	153,243,000	200,000	582,000	153,243,000
Methyl methacrylate	10,000	12,000	18,668,000	100,000	120,000	186,678,000
Methanol	10,000	20,000	2,425,000	100,000	200,000	24,251,000
Dihydrolevoglucosenone	50,000	465,000	35,800,000	200,000	1,860,000	143,200,000
Succinic acid	10,000	20,000	14,065,000	50,000	101,000	70,325,000
Butanediol	10,000	10,100	16,478,000	50,000	51,000	82,391,000
Butanol, acetone and ethanol	50,000	159,000	27,208,000	50,000	159,000	27,208,000
Biosurfactant	50,000	65,000	25,304,000	100,000	130,000	126,518,000
Furandicarboxylic acid	10,000	9,600	6,882,000	50,000	48,000	34,408,000
Acetic acid	200,000	192,000	93,278,000	580000	556,800	270,505,000
TOTAL IMPACT	By 2040			By 2050		
	800,000 tonnes bio-based chemicals	2,305,000 tonnes CO_2e savings	560,700,000 economic value £	2,080,000 tonnes bio-based chemicals	5,231,000 tonnes CO_2e savings	1,570,878,000 economic value £

By 2050, the UK bio-based chemicals industry has the potential to significantly grow, producing over 2 million tonnes of bio-based chemicals, contributing to 5.2million tonnes CO2eq. GHG savings and £1.6bn in value to the UK economy.

Appendix

Table A1: Study Stakeholders

	Organisation	Job Title	Size	Market	Completed survey	Interviewed	Attended workshop June 26th	Attended workshop November 7th
1	2M Group Ltd	Business Development - Biorenewable Materials	Large	Speciality chemicals	■	■	■	
2	Alpek Polyester	Quality Manger	Large	Plastics		■	■	
3	Aquapak Polymers Limited	CTO	SME	Plastics / fibres	■			
4	BASF PLC	Senior Sustainability Manager	Large	Chemicals	■	■	■	■
5	BBSRC	Head of Clean Growth	Government	Biotechnology	■	■	■	
6	BioPak UK Ltd	Technical Director	SME	Consumer products	■	■		
7	Biorenewables Development Centre	Technical Director	SME	Biobased materials		■	■	
8	Bio-Sep (now known as Sonichem)	Commercial Director	Large	Biobased materials	■	■	■	
9	Blank	CEO	SME	Commodity chemicals	■			
10	BP	Head of Advanced Materials and Recycling	Large	Chemicals	■	■	■	
11	Britest	Technical Services Director	SME	Biotechnology	■	■	■	
12	Cellucomp	CEO	SME	Paper and coatings		■	■	
13	Celtic Renewables	CEO	SME	Biobased chemicals	■	■	■	■
14	Chemian Technology Limited	Managing Director	SME	Speciality chemicals	■	■	■	
15	Circa Group	General Manager	SME	Biobased materials	■	■	■	■
16	Composites UK	Sustainability Manager	Trade Body	Composites		■		
17	Constructive Biology Limited	CEO	SME	Biotechnology	■			
18	Corteva Agriscience	Biologicals Portfolio Technology Leader	Large	Agrochemicals	■	■	■	
19	CPI	Director of Biotechnology	Large	Biotechnology	■	■	■	
20	Croda International Plc	Technology Development Lead	Large	Speciality chemicals	■	■	■	■
21	Cromwell Polythene Limited	Managing Director	SME	Consumer products	■			
22	Endeavour Speciality Chemicals	General Manager	SME	Speciality chemicals	■	■		
23	Ensus	Commercial Manager	SME	Commodity chemicals	■	■	■	■
24	Erthos inc	Sustainability and Compliance Manager	SME	Speciality chemicals	■	■		
25	Exxon Mobil	Global Business Development Director	Large	Chemicals		■		
26	Fiberight Ltd	Head of R&D	SME	Speciality chemicals	■	■	■	■
27	Fine chemical	R&D manager	Large	Speciality chemicals	■			
28	Floreon	CSO	SME	Bioplastics		■		
29	Futamura	Sustainability manager	Large	Biobased materials	■	■		
30	GEO Specialty Chemicals	Sustainability Manager	SME	Chemicals		■		
31	Green Rose Chemistry	CEO	SME	Biotechnology		■		■

32	Heriot-Watt University	Student	Large	Biotechnology				
33	Holiferm ltd	Managing Director	SME	Speciality chemicals				
34	Horizon Proteins	CTO	SME	Protein				
35	IBioIC	Senior Business Engagement Manager	SME	Biotechnology				
36	INEOS	Head of Business Development & Sustainability	Large	Commodity chemicals				
37	Infineum UK Limited	Chief Scientist	Large	Speciality chemicals				
38	Ingenza Limited	Head of Chemical Biology	SME	Biotechnology				
39	Ingevity	Director of Innovation	Large	Chemicals				
40	Innovate UK	Deputy Challenge Director	Large	Biobased materials				
41	Johnson Matthey	Senior Principal Scientist	Large	Chemicals				
42	Lignum	CTO	SME	Biobased materials				
43	Manchester Institute of Biotechnology	Director of Commercialisation	Large	Biotechnology				
44	Marine Biopolymers	CEO	SME	Biobased materials				
45	Natwest Bank	Head of Climate Change	Large	Banking				
46	National Farmers Union	Chief Adviser, Renewable Energy and Climate Change	SME	Agriculture				
47	NovaBiochem	CEO	SME	Speciality chemicals				
48	Novamont	Group Sustainability Manager	Large	Chemicals				
49	Oceanium	Corporate Affairs Director	SME	Biobased materials				
50	Oxford Biotrans / HydRegen	MD (Biotrans) / Commercial lead (HydRegen)	SME	Speciality chemicals				
51	PANGAIA Materials Science Ltd.	Head of Materials & Process Innovation	SME	Biobased materials				
52	Parkside Flexibles	NPD Technical Manager	SME	Plastics				
53	Prickly Thistle Scotland Ltd	Founder	SME	Consumer products				
54	Seqens	Plant Manager	Large	Chemicals				
55	Shell	CSO	Large	Chemicals				
56	Society of Chemical Industry	Head of Innovation	SME	Chemicals				
57	Straw Innovations	Director	SME	Biobased materials				
58	Teesside University	Business Innovation Manager - Net Zero	Large	Biotechnology				
59	Thomas Swan & Co. Ltd.	Technical Director & Sustainability Project Manager	SME	Speciality chemicals				
60	UCL	Professor	Large	Biotechnology				
61	UKRI	Head of Circular Economy	Large	Circular Economy				
62	Unilever R&D	Biosourcing Manager	Large	Consumer products				
63	University of Edinburgh	Professor of Sustainable Biotechnology	Large	Biotechnology				
64	University of Nottingham	Assistant Professor	Large	Speciality chemicals				
65	Unknown	Unknown	Large	Plastics / fibres				
66	Unknown	Chemist	Large	Pharmaceuticals				
67	Unknown	Unknown	SME	Unknown				
68	Unknown	Unknown	SME	Unknown				
69	Victrex	Chief Scientist	Large	Plastics / fibres				

Table A2: Long list of chemicals and materials with potential for manufacture from biomass

Carbon Dioxide
3-Hydroxybutryolactone
Acetaldehyde
Acetic Acid/Anhydride
Acetoin
Acetone
Aconitic Acid
Alanine
Ascorbic
Aspartic Acid
Aspartic Acid
Azelaic acid
Butanediol (1,4-)
Butanol (n-)
Carbon Monoxide
Cellulose
Citric Acid
Ethanol
Ethylene
Ethylene Glycol/Oxide
Fatty Alcohols
Formic Acid
Fructose
Fumaric Acid
Furandicarboxylic Acid (2,5-)/HMF/
Furfural
Glucaric Acid
Gluconic Acid
Glucose
Glutamic Acid
Glutaric Acid
Glycerol/Glycerin
Glycine
hemicellulose sugars - galactose
hemicellulose sugars - mannose
Hemicellulose sugars - xylose
Hydrocarbons
Hydrogen
Hydroquinone
Hydroxybutyrolactone (3-)
Hydroxypropionic Acid (3-)
Isoprene
Itaconic Acid
Kojic and Comeric acid
Lactic Acid/Ethyl Lactate
Levoglucosenone
Levulinic Acid
Lignin
Lysine
Malic Acid
Malonic Acid
Methanol
Methyl methacrylate
Muconic Acid
Oxalic Acid
Pelargonic Acid
p-menthane 3,8 diol
Proline
Propane (1,3-)
Propionic Acid
Propylene Glycol
Serine
Simple sugars
Sodium Alginate
Sorbitol
Succinic Acid (1,4-)
Threonine
Xylene
Xylitol/Arabitol

ANNEX 3

Bio-based chemical selection

Selection of Bio-based Chemical Targets

Prepared for the Dept. for Energy Security and Net Zero

This report should be read in conjunction with associated reports as part of project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

February 2024

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Disclaimer

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NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products.

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1 Glossary

Anaerobic digestion: In anaerobic digestion, organic matter is degraded by a microbial population in the absence of oxygen to produce methane and carbon dioxide, plus a solid residue referred to as digestate.

Bio-attributed: The term “bio-attributed” indicates that the use of bio-based feedstock has been ascribed, using a mass balance methodology, to a product. It should not be confused with bio-based, where biomass has been directly used to produce the product.

Bio-based: Means derived from biomass. Biomass can undergo physical, chemical or biological treatment(s).

Bio-based product: A product wholly or partly derived from biomass.

Biofactory: A manufacturing facility used for the conversion of biomass into value-added bio-based products.

Biomass: Material of biological origin, excluding fossilized material and/or material embedded in geological formations.

Biorefining: Biorefining refers to the processing of biomass into a spectrum of marketable products (e.g., food, feed, materials, chemicals) and energy (i.e., fuels, power, heat).

Biorefinery: A large scale production facility undertaking biorefining activities.

Decarbonisation: Reducing or eliminating carbon dioxide emissions associated with energy by replacing high greenhouse gas emission sources with lower greenhouse gas emission alternatives, often by replacing fossil fuel energy with renewable energy sources.

Intermediate chemicals: A broad group of commodity chemicals derived from primary chemicals and used directly, or further processed, to produce polymers and fine and speciality chemicals. Examples of intermediate chemicals include monoethylene glycol, acrylonitrile, styrene and aniline.

Defossilisation: Replacing fossil-based carbon feedstocks with non-fossil, renewable carbon sources.

Fermentation: Biochemical reactions controlled by microorganisms e.g., the transformation of sugar into ethanol.

Green carbon: Carbon of non-virgin fossil carbon origin that can be used as feedstocks to produce chemicals, used in a circular manner with low environmental impacts e.g., sustainably sourced renewable and recycled carbon.

High value chemicals: All chemicals excluding ammonia and methanol.

Mass balance: A chain of custody approach based on tracking the net amount of a material that moves through a system or supply chain and allows an appropriate allocation of this material into finished goods based on auditable bookkeeping.

Methanol economy: A concept where methanol replaces fossil fuels as a means of energy storage, transport fuel, and as a feedstock for the manufacture of high value chemicals.

Platform chemicals: Chemicals that can serve as a substrate for the production of various other higher value-added products.

Primary chemicals: Primary chemicals include ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol.

Renewable carbon: Non-fossil-based sources of carbon that can be used as feedstocks to produce chemicals, used in a circular manner with low environmental impacts e.g., sustainably sourced atmospheric and biogenic carbon.

2 Background

In December 2022, the Department for Energy Security and Net Zero (formerly BEIS) commissioned a 12-month independent study to assess the economic and climate benefits to the UK of an increased use of bio-based chemicals and materials. The research was expected to highlight areas in which biomass use in the chemicals and materials sectors could best contribute to growing innovation and the economy, while also helping meet the UK's Net Zero ambitions.

2.1 Overall Study Approach & Method

The research methodology to address these questions consisted of four strands: a literature review; original research involving stakeholder engagement; quantitative economic and environmental analysis; and a synthesis of finding and reporting.

A literature review, including grey literature was conducted with a focus on existing and nascent technologies for producing bio-based chemicals and materials. The extensive review covered numerous aspects of bio-based chemicals and plastics research and innovation, including but not limited to relevant environmental and economic information.

Industry and academic stakeholders were engaged in original research via one-to-one interviews and online surveys to elicit expert opinion on the UK's current status, opportunities and challenges, and future scenarios for bio-based chemicals production in the UK. A series of briefing sessions and promotion via social media was used to raise awareness of the study. One-to-one interviews with strategically important stakeholders spanning industry, policy and academia gathered in-depth information regarding a) the current status of bio-based chemical production in the UK; b) opportunities and challenges and c) future scenarios for bio-based chemical production in the UK. Stakeholders consulted included large, medium and small businesses, government officials, academics and trade bodies. In total the study engaged with 69 individual organisations. Fifty organisations completed the survey, and 50 organisations were interviewed.

An output from the original research was a list of chemical targets which represented potentially viable, credible and meaningful targets for chemical production in the UK. It should be noted that this chemical list is not intended to be a definitive list of chemicals which the UK should target, but a realistic list of chemicals for economic and environmental analysis. This report provides a summary of the information, data and rationale behind the selection of chemical targets.

The list of target chemicals provided the basis for quantitative economic and environmental analysis, the results of which are reported separately.

2.2 Chemicals Selection

A long list of 69 potential bio-based chemicals and materials was reduced through stakeholder engagement and expert review (see Stakeholder Engagement Final Report) to 15 example chemicals, based on the following questions:

- Is production credible and achievable? – The UK produces the necessary feedstock and production technologies are available (commercial/demonstration at present for 2030 horizon, demonstration/pilot at present for 2040 horizon, and lab based at present for 2050 horizon).
- Would production be meaningful with regards to greenhouse gas emissions reductions? – Production/demand would be at a sufficiently large scale to make a meaningful carbon savings impact. A production output of 10,000 tonnes per year was considered meaningful.
- Is UK-based production plausible and realistic? – There is clear UK interest in the production or use of the chemical (ideally a UK chemical company producing/using or looking to produce/use).

2.2.1 Assessing Credibility and Achievability

Technology readiness level (TRL) and commercial readiness index (CRI) assessments were used to evaluate the credibility of producing each chemical target and when production may be achieved.

Technology readiness was measured over 9 levels, with the first three levels related to fundamental scientific research, levels four to six related to industrial technology development to achieve pilot scale process testing, and the final three levels measuring progress through demonstration towards commercial readiness. While a technology readiness level of nine may mean a process is technically viable, it may not be economically viable at a given point in time, and therefore, may not be commercially deployed. Alternatively, a process may be deployed only to be withdrawn after several years of operation if the process proves not to be financially viable.

The commercial readiness index looks at the status of processes in respect to their commercial deployment. The CRI used in this study has six levels ranging from a hypothetical commercial proposition equating to TRL one to nine, through to widely deployed processes with well-known technical and economic performance data supporting bank financing.

2.2.2 Ensuring Meaningful Net Zero Impact (Scale of Production)

Each target chemical was reviewed against commercial announcements and through stakeholder interview to ensure that commercial scale production would be meaningful in terms of possible greenhouse gas emission savings, and the potential to contribute towards UK net zero ambitions.

2.2.3 Assessing Plausibility

Extensive stakeholder engagement was undertaken to ensure that the target chemicals are of relevance to UK technology developers, the UK value chain, or as UK relevant novel chemicals. Additionally, UK trade data was reviewed to identify UK import volumes for the target chemicals.

2.2.4 Infrastructure, Demand and Integration Factors

Infrastructure, demand and integration factors were incorporated in the selection process by considering where bio-based chemical production might fit with current activity and infrastructure (e.g., Figure 13), reviewing chemical import data to understand downstream industry needs, and incorporating stakeholder insights on future requirements or opportunities.

The selection process also recognised varied stakeholder views on potential transition pathways. Stakeholders raised the potential to integrate the processing of biomass within existing petrochemical processes through mass balancing approaches, the potential for the development of large biorefinery complexes, and the potential for distributed manufacturing facilities (i.e., biofactories) operating at a lower scale to biorefineries and potentially taking advantage of a specific feedstock availability (e.g., industrial process residues).

The selected chemicals, segmented by manufacturing concepts are shown in Table 18

Table 18. Bio-based chemicals selected to assess the economic and environmental impacts of increased bio-based chemicals production in the UK.

	Manufacturing Scenario	
Biorefinery	**Distributed Manufacturing**	**Mass Balanced Chemicals**
Lactic acid - through fermentation for solvent and polymer production.	**Butanol, acetone and ethanol** – through ABE fermentation for solvent applications.	**Bio-based propane** – from SAF production as a chemical cracker feedstock to produce ethylene or propylene
Monoethylene glycol - through sugar hydrolysis for polymer and surfactant production.	**Biosurfactant** – through fermentation for consumer and industry applications.	**Bio-based naphtha** – from SAF production as a chemical cracker feedstock to produce ethylene or propylene
Ethyl acetate - via ethanol for solvent applications.	**Furandicarboxylic acid (and HMF)** - through sugar chemistry for surfactant and polymer production.	**Bio-based methane** – as a feedstock for acetic acid production.
Ethylene – via ethanol for polymer or glycol production	**Butanediol** - through fermentation for polymer production.	
Methyl methacrylate – though fermentation for polymer production.	**Succinic acid** – through fermentation for polymer production.	
Methanol – from green hydrogen and biogenic CO_2 off gas.	**Dihydrolevoglucosenone** – through sugar chemistry as a novel solvent	

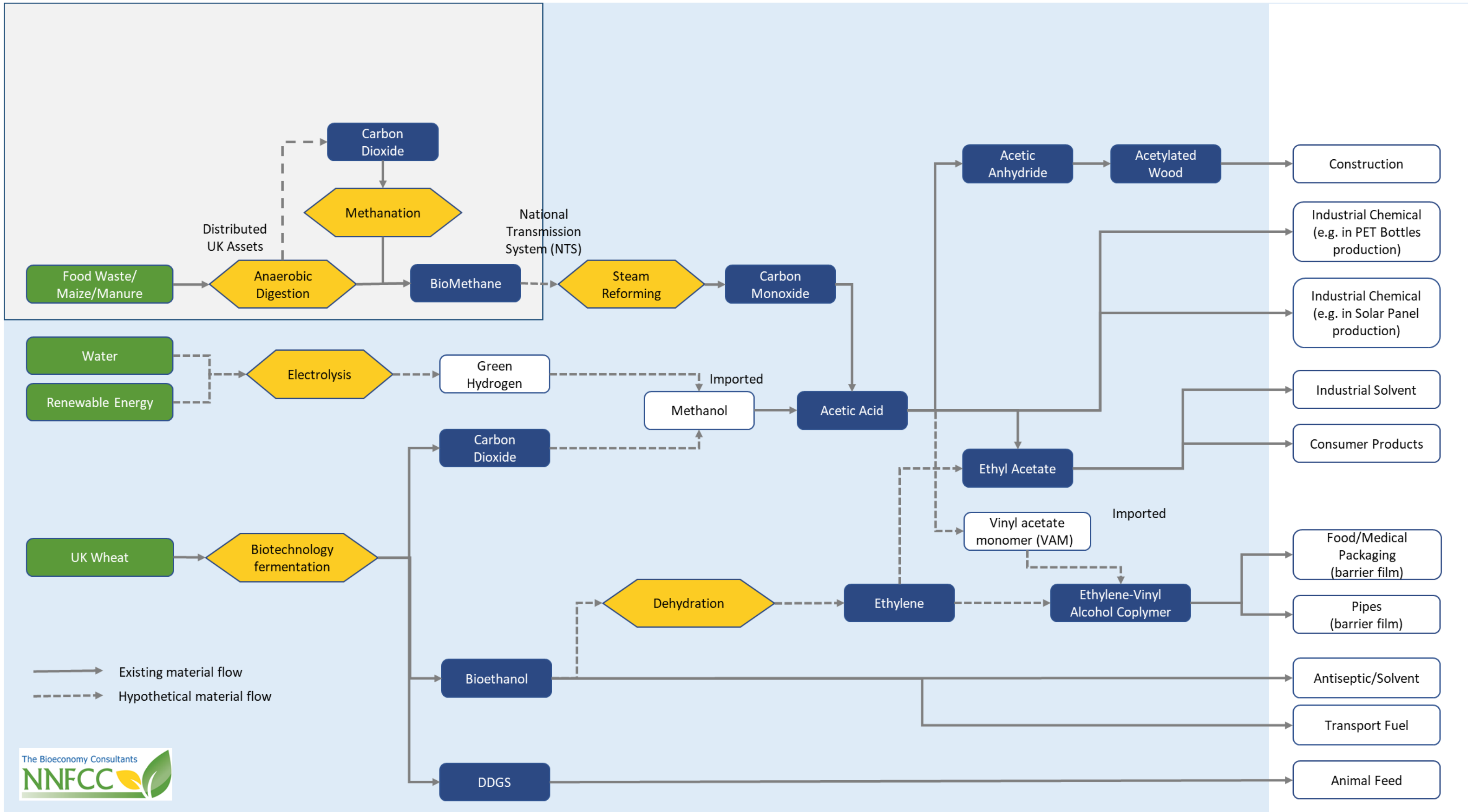

Figure 13. Illustrative example of bio-based chemical integration with existing UK petrochemical manufacturing.

3 Mass Balanced Chemicals

3.1 Introduction

The use of a mass balanced approach in the supply of bio-attributed chemicals allows relatively small quantities of biomass to be used within existing large scale chemical production infrastructure, while deriving maximum value by attributing the renewable input to the product with the largest market demand for renewable content (although there is limited physical biomass carbon content).

Mass balancing avoids the need for large capital investment into new biorefineries and allows bio-attributed products to benefit from economies of scale which would otherwise be difficult to replicate through current biomass feedstock supply chains.

Several companies are utilising the mass balance approach to increase the amount of renewable content in their feedstocks. For example, BASF have taken steps to replace fossil feedstocks with renewable alternatives. At BASF's steam crackers, the point at which its primary chemicals are produced and numerous supply chains begin, renewable material is integrated. This allows a variety of their end products to be mass balanced as renewable, including super absorbents, dispersions, plastics and intermediates. The volume of renewable input is certified by the third-party body, REDcert.[95]

UK based global speciality chemical manufacturer, Croda, use mass balancing as certified by the Roundtable on Sustainable Palm Oil (RSPO) in the production of sustainable palm oil derivatives.[96]

Producers of renewable raw materials can supply the chemical industry who can then benefit from their renewable supply chains. Neste[97] for example, produce 'MY Renewable Naphtha' utilising vegetable oils and waste fats, and UPM's 'BioVerno naphtha'[98] is produced from crude tall oil, a residue of the wood pulp making process.

These feedstocks are finding increasing uses. For example, Borealis,[99] a polyolefin manufacturer, is aiming to employ Neste's naphtha to produce bio-attributed polypropylene. LyondellBasell are too using Neste's feedstocks to produce both bio-based polypropylene and low-density polyethylene (LDPE). Neste and IKEA are collaborating to incorporate bio-attributed polypropylene and polyethylene into the production of IKEA's plastic products.[100]

Multiple players in the chemicals and polymer industry are following suit and finding supply chains that incorporate renewable materials. In 2019, INEOS Inovyn became the world's first commercial

95 BASF, The Mass Balance Approach in Feedstock Substitution, https://www.basf.com/gb/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach.html, [accessed 20 Dec. 2023].
96 Croda, RSPO-certified ingredients for personal care, https://www.crodapersonalcare.com/en-gb/regulations-and-certifications/sustainable-palm-oil-rspo, [accessed 20 Dec. 2023].
97 Neste, Neste Oil adds NExBTL renewable naphtha suitable for producing bioplastics to its corporate customer product range, https://www.neste.com/neste-oil-adds-nexbtl-renewable-naphtha-suitable-producing-bioplastics-its-corporate-customer, [accessed 20 Dec. 2023].
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99 Borealis, The Bornewables™https://www.borealisgroup.com/circular-economy/bornewables [accessed 20 Dec. 2023].
100 Neste, IKEA and Neste take a significant step towards a fossil-free future, https://www.neste.com/releases-and-news/renewable-solutions/ikea-and-neste-take-significant-step-towards-fossil-free-future, [accessed 20 Dec. 2023].

producer of bio-attributed PVC, trademarked as BIOVYN™.[101] In 2022, Inovyn also introduced REODRIN™, the world's first bio-attributed epichlorohydrin.[102]

Sabic are also using the mass balance approach to increase the amount of renewable content in their materials.[103] Sabic have introduced a polycarbonate based on the incorporation of renewable feedstock, which is in addition to their current collection of Trucircle™ polyolefins. Their polycarbonate uses renewable raw materials in combination with virgin fossil resources, co-processed and audited by the ISCC. CEPSA, the Spanish multinational oil and gas company is a key supply chain partner here. Also verified by the ISCC, are some of Sabic's current collection, which includes certified circular polymers that use pyrolysis oil (originating from plastic waste) produced by Plastic Energy Ltd.

Certification is key. Without a proper audit there is no way to demonstrate a link to renewable materials. There are several third-party certification schemes, including the ISCC (International Sustainability and Carbon Certificate)[104], the RSB (Roundtable on Sustainable Biomaterials)[105] and REDcert.[106] The ISCC measures sustainability for food, feed, products and energy across their supply chains, with the option to extend the scope of certification to specific market requirements, such as non-GMO and phasing out hazardous chemicals. Similarly, the RSB ensures supply chains in the bioeconomy are socially responsible, environmentally sustainable and credibly sourced, and the REDcert was initially created for the analysis of biofuels and liquid biomass, but the scope was extended to include sustainable agricultural raw materials in 2015 and the chemical industry in 2018. All three schemes offer different types of certificates depending on the area of focus. For example, the RSB EU RED Standard is specific to biofuel producers in the EU, and the REDcert scheme applies to the chemical industry.

While the mass balance approach has several advantages over dedicated bio-based production, it does have its own issues. In the short-term, it increases the share of renewable resources used as a feedstock because it's easy to adopt and can raise awareness of the potential for producing chemicals and materials from biomass. However, it is also easy to curtail production and may not support a permanent transition to using renewable raw materials. In addition, some stakeholders point out that the consumer could be misled into buying products labelled as 'renewable', or 'bio-based', but physically have little renewable content. It is important that terms such as bio-based and bio-attributed are used consistently and communicated transparently to avoid customer misinterpretation, which could result in a loss of trust in the bio-based industry.

101 Ineos, Biovyn A big step forward towards carbon neutrality, https://biovyn.co.uk/, [accessed 20 Dec. 2023].
102 Ineos, REODRIN™ from INEOS Inovyn, gets ISCC PLUS certification, opening the door to wider market availability, https://www.ineos.com/businesses/inovyn/news/reodrin-from-ineos-inovyn-gets-iscc-plus-certification-opening-the-door-to-wider-market-availability/, [accessed 20 Dec. 2023].
103 SABIC, Trucircle™ portfolio and services, https://www.sabic.com/en/sustainability/sustainable-solutions/trucircle-portfolio-and-services, [accessed 20 Dec. 2023].
104 ISCC, The Mass Balance Approach, https://www.iscc-system.org/certification/chain-of-custody/mass-balance/, [accessed 20 Dec. 2023].
105 RSB, A guide to RSB certification, https://rsb.org/wp-content/uploads/2020/06/RSB-Certification-Guide-2020-update_compressed.pdf, [accessed 20 Dec. 2023].
106 RedCert, Scheme principles for mass balancing, https://www.redcert.org/images/SP_EU_Mass_balancing_Vers.04.pdf, [accessed 20 Dec. 2023].

3.2 Bio-attributed Ethylene from SAF By-products

The UK has an ambition to be a global leader in decarbonising aviation. As described in the Transport Decarbonisation Plan, the Government has committed to net zero aviation by 2050.[107]

The 2022 Jet Zero Strategy set out the Government's plan for achieving net zero aviation, or "jet zero", by 2050. A combination of rapid technology development and ambitious targets is designed to achieve net zero domestic aviation and zero emission airport operations in England by 2040.

A key element of the Jet Zero Strategy is the production, supply and use of Sustainable Aviation Fuel (SAF) produced from low carbon feedstocks. SAF offers lifecycle emissions savings of over 70% when fully replacing fossil derived kerosene and can be used in existing aircraft, engines, and infrastructure without modification. The development of SAF production in the UK supports fuel security, supports economic growth with £742m expected annually by 2035, and will potentially secure up to 5,200 UK jobs by 2035 and a further 13,600 through global exports.[108]

The Government has plans to introduce a SAF mandate from 2025, requiring at least 10% (around 1.5bn litres, or 1.2 million tonnes) of UK aviation fuel to be made from sustainable sources from 2030. Eligible fuels will be waste and residue-derived biofuels, renewable carbon fuels and Power to Liquid (PtL) fuels.

Within the Jet Zero Strategy the ambition is to have at least five commercial-scale SAF plants under construction in the UK by 2025. To date, government funding has been awarded to 14 SAF development projects.[109]

In addition to these planned purpose-built SAF production facilities, the UK also has SAF production capacity through the Phillips 66 Humber refinery. In 2021, British Airways and Phillips 66 signed a multi-year SAF supply agreement. Under the agreement, SAF would be produced at scale for the first time in the UK and be supplied to British Airways to power a number of its flights from early 2022. In 2022, a little over 5 million litres of SAF supplied under the UK's Renewable Transport Fuel Obligation (RTFO) was recorded as being of UK origin.

Each SAF pathway produces hydrocarbon by-products (propane and naphtha) which may be suitable as steam cracker feedstocks to produce primary chemicals such as ethylene and propylene.

Based on the Government's ambition to have five operating plants by 2030 and their proposed refinery capacities (plus existing capacity), a reasonable scenario for UK SAF production by 2030 would

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107 Dept for Transport, 2022, Jet Zero strategy: delivering net zero aviation by 2050, https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050, [accessed 20 Dec. 2023].
108 Dept for Transport, Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147350/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate.pdf, [accessed 20 Dec. 2023].
109 Dept for Transport, Advanced Fuels Fund (AFF) competition winners https://www.gov.uk/government/publications/advanced-fuels-fund-competition-winners/advanced-fuels-fund-aff-competition-winners, [accessed 20 Dec. 2023].

be 500-750 million litres, equating to 410-615 thousand tonnes of fuel, and approximately one-third to a half of all fuel demand under the SAF mandate.

Although hydrocarbon by-products may be produced during SAF production, whether they are recovered and sold depends on the cost of recovery and their alternative uses in providing process energy within the plant. However, based on a 5% recovery rate it is reasonable to suggest that a modest 20-30 thousand tonnes of tonnes of hydrocarbons could be made available as a renewable (biogenic or recycled) feedstock for the chemical industry. Although, it should be noted that both Fisher-Tropsch and Alcohol-to-Jet processes could be designed to produce more light-hydrocarbon products should the market demand exist.

3.2.1 Technology and Commercial Readiness

Bio-based propane and naphtha is produced during the conversion of vegetable oils to hydrogenated vegetable oil (HVO diesel) and hydroprocessed esters and fatty Acids (HEFA aviation fuel), processes that are used commercially by several chemical companies. This demonstrates a technology readiness of 9 and a commercial readiness of 3.

3.2.2 UK Relevance

The UK is home to three large steam crackers, the Ineos KG cracker at Grangemouth, the Sabic Olefins 6 cracker at Wilton, and the ExxonMobil ethylene plant in Fife.

The Ineos KG cracker runs on cost advantaged feedstock (ethane) extracted from North American shale gas and shipped to the UK. Ineos began the import of ethane in 2016 under long-term contracts (15 years) with US shale gas producers.[110] The cracker produces feedstock for two co-located polymer plants, Innovene 4 (polyethylene) and PP3 (polypropylene) as well as a synthetic ethanol plant. The Grangemouth site produces 1.4 million tonnes of chemical products. Ethylene not consumed on site is shipped via the UK's ethylene pipelines to the North East and North West of England for further processing or export.

The Sabic Olefins 6 cracker has not been in operation since the end of September 2020 but is anticipated to be back on-line in middle of 2024[111]. Olefins 6 was originally built as a liquid naphtha cracker but is now being converted to a 'gas cracker'[112] for the processing of ethane feedstock. Olefins 6 produces ethylene, which is used as a raw material at the adjacent Sabic System 18 polyethylene (LDPE) plant (capacity 400,000 tonnes)[113] and for export via the liquefaction and jetty facilities at North Tees. The re-configuration of Olefins 6 will result in a reduced throughput, although the extent of the reduction is unclear. Previous production was in the region of 1,280,000 tonnes of primary products capacity (including 865,000 tonnes of ethylene, plus 415,000 tonnes per year of propylene)[114] with

110 Ineos, Ineos at Grangemouth, https://www.ineos.com/sites/grangemouth/about/, [accessed 20 Dec. 2023].
111 Industrial Stakeholder, Private Communication.
112 Sabic, Wilton Site, https://www.sabic-teesside.co.uk/en/teesside-site/wilton-site, [accessed 20 Dec. 2023].
113 PlastEurope.com, LDPE: Sabic declares force majeure on supply from Wilton, https://www.plasteurope.com/news/LDPE_Sabic_declares_force_majeure_on_supply_from_Wilton_t241757/, [accessed 20 Dec. 2023].
114 ChemManager, SABIC to Sink £850 Million into Wilton Cracker, https://www.chemanager-online.com/en/news/sabic-sink-ps850-million-wilton-cracker, [accessed 20 Dec. 2023].

around another 1,000,000 tonnes of co-products (predominantly gasoline and mixed C4s) and materials recycled for use as fuel (e.g., methane).[115]

The ExxonMobil cracker uses natural gas liquids from the North Sea as its raw material. The plant was originally designed to produce 500,000 tonnes of ethylene every year, however it now has an annual production of approximately 830,000 tonnes.[116]

Both Ineos and Sabic operate mass balance programs to convert biomass feedstocks into bio-attributed products (see mass balance section). Although the UK's gas crackers may not be capable of processing naphtha feeds (and therefore not capable of taking naphtha as a by-product of SAF production), there may be the potential to process propane which could be mass balanced into the production of bio-attributed polyethylene or propylene for domestic sale or export.

3.2.3 SWOT analysis

Figure 14. SWOT analysis for UK production of ethylene based on SAF by-product propane as a steam cracker feedstock.

3.3 Bio-attributed Acetic Acid/Acetic Anhydride via Biomethane

The Ineos Acetyls plant at Saltend, Hull, is the largest acetic acid, acetic anhydride and ethyl acetate plant in Europe. It is also home to the business's global technology development and support team.[117]

The Saltend plant produces acetic acid through the formylation of methanol with carbon monoxide produced from natural gas (methane). The plant consumes 4 TWh of natural gas annually, of which 68% is used as a feedstock to produce acetic acid.[118]

115 Environment Agency, Variation application number EPR/BS3590IE/V015, https://assets.publishing.service.gov.uk/media/620dff368fa8f549071fc6c2/Variation_Notice_BS3590IE-V015.pdf, [accessed 20 Dec. 2023].
116 ExxonMobil, Your guide to the Fife Ethylene plant https://mossmorran.org.uk/wp-content/uploads/2017/07/FEP_brochure.pdf; [accessed 01 Feb 2023]
117 Ineos, Hull, https://www.ineos.com/sites/hull/, [accessed 20 Dec. 2023].
118 Ineos, Personal Communication, 2023

3.3.1 Biomethane

Biomethane (also known as renewable methane, or bio-based methane) is chemically identical to methane derived from natural gas, or produced during the refining of crude oil, and could be used as a direct replacement. Biomethane is produced through anaerobic digestion (AD). The AD process starts when bioresources (feedstock) such as food waste, manure, crops and crop wastes are fed into an anaerobic digester. Often a pre-treatment step is needed, either to remove packaging materials (e.g., from supermarket food waste) or to make materials more available for biological breakdown.

The core of the process consists of a tank (digester) or a series of tanks, into which suitable feedstocks are fed regularly and mixed into the microorganism-rich liquid or slurry already present inside the digester. Microorganisms break down the materials in a series of biological reactions, resulting in biogas, a combination of methane (CH_4) and carbon dioxide (CO_2), with a typical methane content of 50-70% depending on the feedstock used. Methane yields can be enhanced through various biomethanation processes, where hydrogen is used to convert carbon dioxide to methane.[119]

There are three common end-uses for biogas:

- Combined Heat and Power (CHP): biogas is combusted in a combined heat and power (CHP) unit to make electricity and useful heat.
- Heat: biogas is combusted to generate only heat.
- Biogas up-grading: biogas is upgraded to biomethane, which can then be injected into the gas grid, and/or used for heating, transport or chemical processing.

According to NNFCC's 'AD Deployment in the UK Database',[120] there are 615 AD plants operating within the United Kingdom at present. Of these, it is understood that 408 sites are primarily farm-fed (with a cumulative installed electrical capacity of 243.6 MWe), while 207 are waste-fed facilities (with a cumulative installed electrical capacity of 327.3 MWe). It is estimated that a further 180 sewage treatment AD plants are also operational across the UK bringing the total number of operational facilities to 795.

Of the AD plants that are now operational in the UK, 173 are small-scale plants (with a cumulative installed electrical capacity of 24.2 MWe), 166 are medium-scale plants (with a cumulative installed electrical capacity of 79.0 MWe), and 141 are large-scale plants (with a cumulative installed capacity of 270.4 MWe). There are a further 126 biogas-to-grid (BtG) plants currently in operation across the UK, which are believed to contribute a further 196.7 MWe of installed electrical capacity as well as 58,825 Nm3/hr of biomethane capacity. An additional 9 plants are classified under 'other' output type.

The latest addition to UK AD capacity was a waste-fed, biomethane-to-grid (BtG) with combined heat and power (CHP) facility with 500 kW of electrical capacity partially used on site and partially exported to the grid, and a 1,000 Nm^3/hr biomethane capacity.

119 Bywater, A.; Heaven, S.; Zhang, Y.; Banks, C.J. Potential for Biomethanisation of CO2 from Anaerobic Digestion of Organic Wastes in the United Kingdom. Processes 2022, 10, 1202. https:// doi.org/10.3390/pr10061202
120 NNFCC, Anaerobic Digestion Deployment in the UK, 2023.

3.3.2 Technology and Commercial Readiness

Biomethane is widely produced and placed onto the UK's gas grid. Biomethane has not been used to replace natural gas in the production of acetic acid from methanol, although this is due to financial considerations rather than technology constraints. This corresponds to a technology readiness of 9 and a commercial readiness of 1, although commercial readiness could rapidly increase.

3.3.3 UK Relevance

In 2022, 6.2 TWh of biomethane was injected into the GB gas grid through AD. However the amount of biogas (landfill, sewage and anaerobic digestion) used to generate electricity (i.e., not upgraded to biomethane) was 21 TWh.

Through a mass balancing mechanism, biomethane could be used to produce bio-attributed acetic acid and derivatives. This biomethane application would lock biogenic carbon into acetic acid and derivatives, such as acetic anhydride. If acetic anhydride was used in the acetylation of wood products for construction, this would result in long term carbon storage.[121]

3.3.4 SWOT Analysis

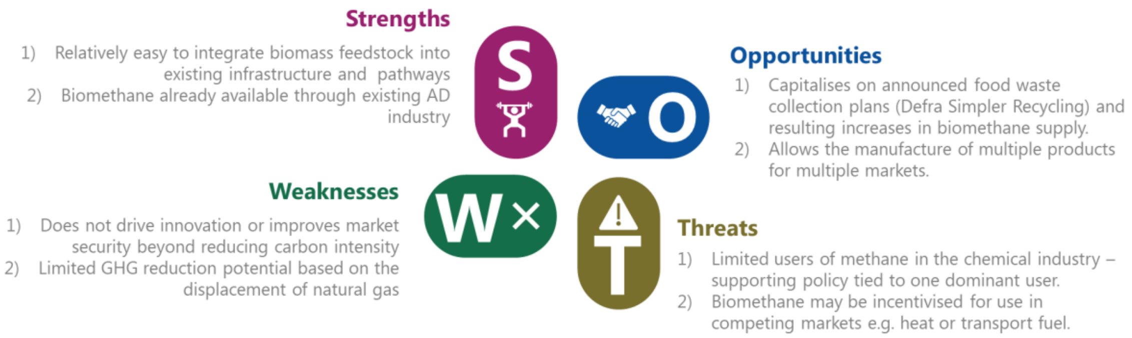

Figure 15. SWOT analysis for UK production of acetic acid incorporating UK biomethane feedstock.

4 Biorefinery Chemicals

4.1 Introduction

A biorefinery is a facility that integrates various biomass conversion processes to produce a range of bio-based products and bioenergy. The goal of a biorefinery is to efficiently convert biomass into a variety of valuable products, including biofuels, chemicals, materials, and energy.

121 Accsys, World-first Tricoya® plant construction milestone: 9-storey acetylation tower ascends to full height, https://www.accsysplc.com/world-first-tricoya-plant-construction-milestone-9-storey-acetylation-tower-ascends-to-full-height/, [accessed 20 Dec. 2023].

The processes within a biorefinery can be categorized into three main types:

- Biochemical Processes: These involve the use of microorganisms or enzymes to break down biomass into various products. Common examples include fermentation to produce bioethanol or biogas, and enzymatic processes to convert biomass into sugars.
- Thermochemical Processes: These processes use heat, pressure, and/or catalysts to convert biomass into different products. Pyrolysis, gasification, and torrefaction are examples of thermochemical processes that can produce bio-oil, syngas, or solid biochar.
- Mechanical/Physical Processes: These involve mechanical and physical methods to extract valuable components from biomass. Mechanical pressing, grinding, and extraction processes are used to obtain oils, fibres, or other valuable materials.

The integration of these processes allows a biorefinery to maximize the value derived from biomass feedstocks while minimizing waste. Biorefineries can be seen as central to a transition from the use of fossil resources to renewable biomass in providing the platform chemicals on which the downstream chemical and material industries, and chemical using industries rely. Biorefineries are also sources of important products outside of the chemical and fuel industries e.g., crop-based bioethanol refineries are an important of source of protein for livestock, and pet consumption.[122, 123]

4.2 Lactic Acid (Polylactic acid)

Lactic acid and its derivatives are used in a range of applications e.g., as ingredients in the food and beverage (FAB) industry, in personal care formulations, as building blocks in the pharmaceutical industry and in polylactic acid (PLA) polymer production.

Global demand for lactic acid is estimated to be around 1.2 million tonnes in 2023, with a market value of around US$1.6bn.[124]

Lactic acid's largest market segment is in the production of PLA, a bio-based, industrially compostable polymer with the potential to displace various fossil-based plastics. Global PLA production is considered to be around 350,000 tonnes[125] although capacity has been assessed to be considerably higher at 676,000 tonnes.[126]

Globally two companies dominate the PLA market, American company, Natureworks,[127] and TotalEnergies Corbion,[128] a joint venture between Dutch lactic acid producer, Corbion, and the French energy company, Total.

122 Ensus, DDGS Distillers' Dried Grains with Solubles, https://www.cropenergies.com/en/products/food-and-animal-feed/ensus-ddgs, [accessed 20 Dec. 2023].
123 CropEnergies, CropEnergies invests more than EUR 100 million in UK production site, https://www.cropenergies.com/en/press/details/cropenergies-invests-more-than-eur-100-million-in-uk-production-site, [accessed 20 Dec. 2023].
124 NNFCC analysis, 2023.
125 ChemAnalyst, Decode the future of Polylactic acid, https://www.chemanalyst.com/industry-report/polylactic-acid-pla-market-673#, [accessed 02 Jan. 2024].
126 European Bioplastics, Bioplastics market development update 2023 https://www.european-bioplastics.org/market/, [accessed 02 Jan. 2024].
127 Natureworks, https://www.natureworksllc.com/, [accessed 02 Jan. 2024].
128 TotalEnergies Corbion, https://www.totalenergies-corbion.com/, [accessed 02 Jan. 2024].

4.2.1 Technology and Commercial Readiness

Lactic acid is produced at scales over 100,000 tonnes using sugar/starch feedstocks at multiple sites globally. Technology readiness is 9 and commercial readiness is 5. However, production based on biogenic municipal solid waste is technology readiness 8 and commercial readiness 1.

4.2.2 UK Relevance

There are no lactic acid or PLA producers currently located in the UK. However, the UK does have a PLA using industry which would be expected to grow should UK policy support the use of compostable materials in optimising the recovery and recycling of biogenic waste e.g., food waste. Consultants, Ricardo, in conjunction with BBIA members estimated that 1,600 tonnes of PLA were placed on the UK market in 2018. However, Ricardo estimated that with supporting policies, the UK market potential for compostable plastic could lie between 90,000-138,000 tonnes, based on the potential to substitute existing plastic use. Based on a 20% PLA share of the compostable plastic in the UK, the PLA market could grow to exceed 27,000 tonnes.[129] In 2023, Defra announced its plans for 'Simpler recycling' collections which included the requirement for weekly collections of food waste to be introduced for most households across England by 2026.[130] Increasing food waste collections has the potential to increase the demand for compostable caddy liners and provide a wide spread disposal route for compostable materials including PLA.

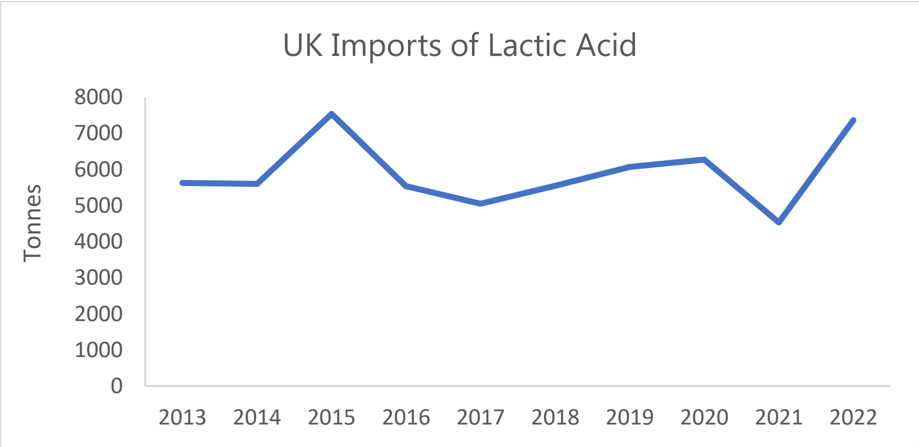

Figure 16. UK imports of lactic acid.[131]

Floreon,[132] based in Hull, uses PLA as a base polymer in the production of their range of bio-based plastics. Through the optimised use of additives, Floreon produce a PLA plastic ten times tougher than acrylonitrile butadiene styrene (ABS).

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129 Ricardo, Plastics in the Bioeconomy, 2019, https://bbia.org.uk/wp-content/uploads/2019/05/Plastics-in-the-Bioeconomy-report-1.pdf, [accessed 20 Dec. 2023].
130 Defra, Simpler recycling collections and tougher regulation to reform waste system, https://www.gov.uk/government/news/simpler-recycling-collections-and-tougher-regulation-to-reform-waste-system, [accessed 02 Jan. 2024].
131 HM Revenue and Customs https://www.uktradeinfo.com/trade-data/, [accessed 02 Jan. 2024].
132 Floreon, https://www.floreon.com/, [accessed 02 Jan. 2024].

Companies such as BioPak[133] and Scottish based compostable packaging supplier Vegware,[134] use PLA to produce clear catering products like cold cups and deli containers, and as a liner in board-based products.

4.2.3 SWOT Analysis

Figure 17. SWOT analysis of UK lactic acid production from fermentable sugars.

4.3 Monoethylene Glycol

Monoethylene glycol (MEG) has a market size of around 28 million tonnes and is used in a range of industrial and commercial applications.[135] MEG is a key component in many automotive antifreeze formulations, it is also used in de-icing solutions for aircraft, runways, and roads. Additional applications include heat transfer fluids, hydraulic fluids and in the dyeing and finishing of textiles.

Around 75% of all MEG production is consumed in the production of polyester fibres, films, and resins, such as polyethene terephthalate (PET) for textile and packaging applications. It is also used in the production of alkyd-type resins.[136]

Bio-based MEG can be produced via the dehydration of ethanol to ethylene, followed by oxidation to ethylene oxide, and subsequently to MEG. Greencol Taiwan Corporation (GTC) has operated a bio-based MEG plant with a 75,000 tonne per year capacity at Kaohsiung, Taiwan, since 2013. GTC is a 50:50 joint venture between Nagoya-based Toyota Tsusho Corporation (TTC) and Taipei-based China Man-Made Fiber Corporation. The MEG plant is co-located with a 100,000 tonne per year bio-based ethylene plant.

133 BioPak, https://www.biopak.com/uk/, [accessed 02 Jan. 2024].
134 Vegware. https://www.vegware.com/uk-en/, [accessed 02 Jan. 2024].
135 Chem Analyst, Decode the future of monoethylene glycol, https://www.chemanalyst.com/industry-report/mono-ethylene-glycol-meg-market-646, [accessed 02 Jan. 2024].
136 Data Bridge Market Research, Global Monoethylene Glycol Market https://www.databridgemarketresearch.com/news/global-monoethylene-glycol-market, [accessed 02 Jan. 2024].

Alternatively, companies are commercializing processes to produce MEG directly from sugars. In 2019, Avantium opened a 10 tonne per year plant to demonstrate the production of bio-based MEG using their one-step hydrogenolysis Ray Technology™.[137]

Brazilian chemical company Braskem and Sojitz Corporation are collaborating in a joint venture project named Sustainea[138], the companies are aiming to construct three industrial plants with annual production capacity of 700,000 tonnes of renewable MEG.

UPM Biochemicals has developed its own process to produce MEG from hard wood residues. The company is currently building a biorefinery in Germany with capacity to produce 220,000 tonnes of MEG, propylene glycol, industrial sugars, and lignin products.

4.3.1 Technology and Commercial Readiness

Monoethylene glycol production using sugar from a range of biomass feedstocks is being demonstrated by several companies globally. Commercial production facilities are in planning and construction. Technology readiness is 9 and commercial readiness is 2.

4.3.2 UK Relevance

UK production of MEG ceased in 2010 with the closure of Dow Chemical's ethylene oxide and ethylene glycol (EOEG) production facility at Wilton.[139] The closure resulted in the simultaneous closure of a Croda surfactants production plant which relied on the ethylene oxide feed.

MEG has been cited by industry stakeholders[140] as a key chemical intermediate in the production of polyesters and surfactants.

The UK has demand for 340,000 tonnes of PET pellets. Alpek Polyester manufactures 200,000 tonnes of fossil-based PET per year, the monoethylene glycol and terephthalic acid required for production are imported.

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137 Avantium, Avantium advances its plant-based MEG technology with the opening of its demonstration plant, https://www.avantium.com/wp-content/uploads/2019/11/20191107-Press-release-Avantium-advances-its-plant-based-MEG-technology-with-the-opening-of-its-demonstration-plant-final.pdf, [accessed 02 Jan. 2024].
138 Braskem, https://www.braskem.com.br/news-detail/braskem--and-sojitz-corporation-launch-sustainea, [accessed 31 Jan. 2024].
139 PlasteMart, Dow to shut UK ethylene oxide & glycol plant by Jan 2010 end, https://www.plastemart.com/news-plastics-information/dow-to-shut-uk-ethylene-oxide-glycol-plant-by-jan-2010-end/15782 [accessed 02 Jan. 2024].
140 Stakeholder feedback as part of this study, 2023.

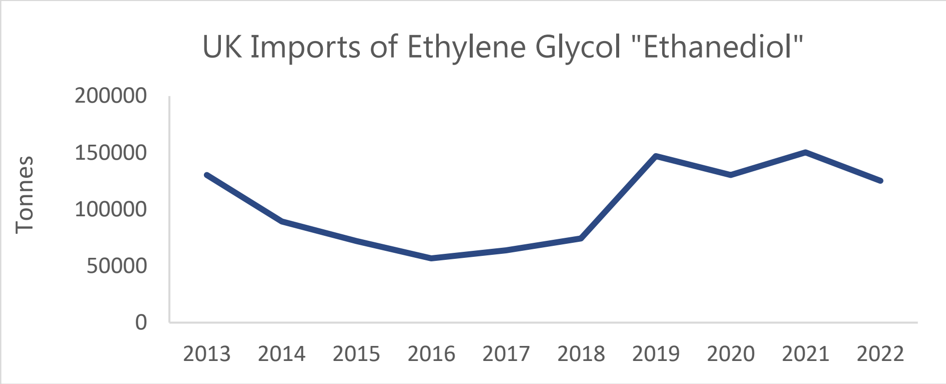

Figure 18. UK imports of ethylene glycol.[141]

4.3.3 SWOT Analysis

Figure 19. SWOT analysis for UK MEG production by chemical conversion of cellulosic sugar.

4.4 Ethyl Acetate

Global ethyl acetate market demand currently stands at around 4-5 million tonnes per year with a near term CAGR of 3.5-4%. Ethyl acetate's market value is assessed to be in the order of US$3-6bn, growing at a CAGR of 6%.

There are various methods for manufacturing ethyl acetate. Commercial processes include: Fischer esterification which involves reacting acetic acid with ethanol in the presence of an acid catalyst; the Tishchenko method which involves condensing two equivalents of acetaldehyde in the presence of an alkoxide catalyst; and by the direct addition of acetic acid to ethylene in the presence of a strong acid.

141 HM Revenue and Customs https://www.uktradeinfo.com/trade-data/ [accessed 02 Jan. 2024].

Located at Saltend, Hull, Ineos Acetyls is the largest producer of acetic acid, acetic anhydride and ethyl acetate in Europe, and is home to the business's global technology development and support team.[142] The Saltend site has an ethyl acetate production capacity of 280,000 tonnes per year.

Bio-based ethyl acetate could be produced through the reaction of bio-based acetic acid with bio-based ethylene (as operated by Ineos Acetyls). Alternatively, it could be produced from bio-based ethanol. Johnson Matthey has developed a process that enables ethyl acetate and a valuable hydrogen by-product stream to be produced directly from ethanol.[143] In the process, dry ethanol is dehydrogenated to produce a crude ethyl acetate stream. This is selectively hydrogenated to remove by-products that cannot be separated by distillation. A final refining section then splits the azeotrope to produce a high purity ethyl acetate product. Unreacted ethanol is recycled to a dehydration unit where it is combined with fresh ethanol.

The owner of UK based bio-based ethanol producer Ensus, CropEnergies AG, announced in December 2022, its intention to build an ethyl acetate plant based on ethanol.[144] The anticipated location is the Zeitz Chemical and Industrial Park, Elsteraue, Germany. With a total investment of between EUR 120-130 million, work on the 50,000 tonnes per year plant is expected take place early in 2024 with commissioning scheduled for summer 2025.

4.4.1 Technology and Commercial Readiness

Ethyl acetate production via ethanol condensation is a licensed technology. Commercial production facilities are in construction. Technology readiness is 9 and commercial readiness is 2.

4.4.2 UK Relevance

At its two world-scale bio-based ethanol plants, based on Teesside and the Humber, the UK has a bio-based ethanol production capacity of 650,000 tonnes. This capacity represents an ethyl acetate production potential of 550,000 tonnes.

There is the potential for production in the UK and an interest from Ensus in the production of ethyl acetate based on the ethanol currently produced at its plant on Teesside.

142 Ineos, Hull, https://www.ineos.com/sites/hull/, [accessed 21 Dec. 2023].
143 Johnson Matthey, Ethyl acetate process, https://matthey.com/products-and-markets/chemicals/process-licensing/ethyl-acetate-process, [accessed 21 Dec. 2023].
144 Crop Energies, CropEnergies to build renewable ethyl acetate plant near Zeitz, https://www.cropenergies.com/en/press/details/cropenergies-to-build-renewable-ethyl-acetat-plant-near-zeitz, [accessed 21 Dec. 2023].

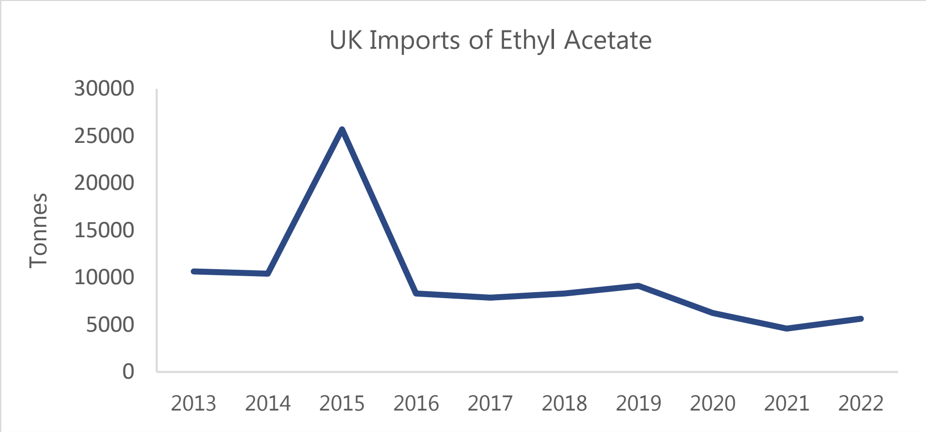

Figure 20. UK import of ethyl acetate.[145]

4.4.3 SWOT Analysis

Figure 21. SWOT analysis for production of Ethyl Acetate from UK ethanol assets.

4.5 Ethylene

Ethylene is one of the key building blocks of the petrochemical industry. Global ethylene production capacity stands at over 200 million tonnes, making ethylene the world's largest petrochemical by volume. Ethylene forms the basis of the production of polyethene (including high density (HDPE), low density (LDPE) and linear low density (LLDPE)), polystyrene (PS), polyvinyl chloride (PVC), ethylene oxide and a range of other chemicals and polymers.

Bio-based ethylene is accessible via the dehydration of bio-based ethanol. The scope of the ethanol/ethylene value is shown in Figure 22 and demonstrates the potential of bio-based ethanol as a platform of the chemical industry.

145 HM Revenue and Customs https://www.uktradeinfo.com/trade-data/ [accessed 21 Dec. 2023].

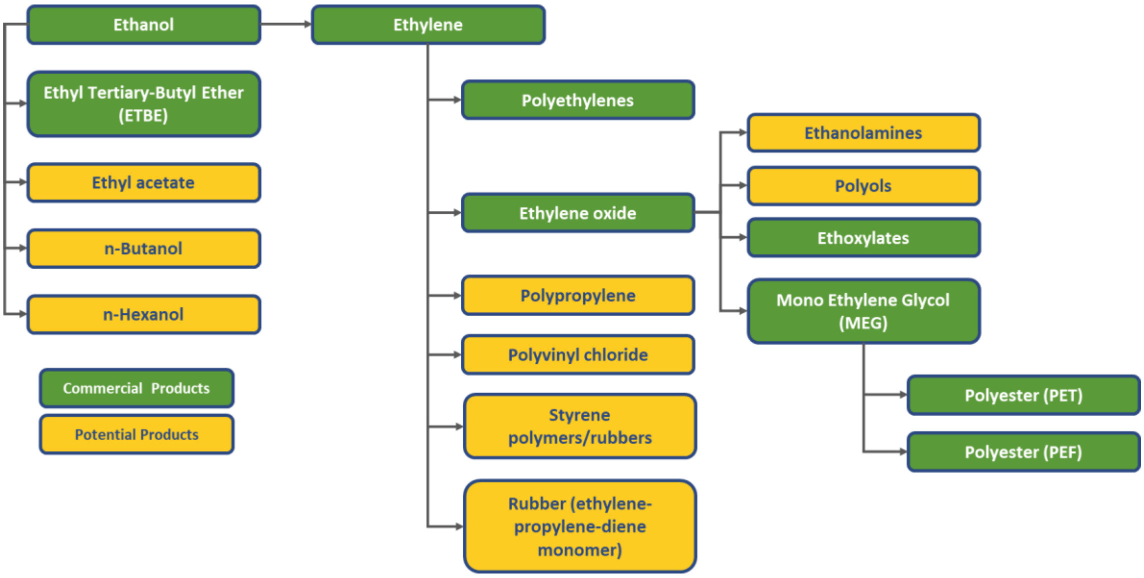

Figure 22. Ethanol and ethylene value chain

Bio-based ethylene is produced and converted to a range of products by Brazilian based chemical company Braskem. As of 2023, Braskem have an operating capacity of 260,000 tonnes per year of bio-based ethylene.[146] Braskem offers a range of bio-based ethylene derived materials including HDPE, LLDPE, LDPE and EVA (ethylene-vinyl acetate).

UK speciality chemical company, Croda, produces bio-based ethylene[147] at its Atlas Point facility located in New Castle County, Delaware, U.S. The ethylene, produced from corn derived ethanol, is converted to ethylene oxide which is then used to make surfactants. Croda's surfactants are used by other manufacturers to make a variety of consumer products, such as soaps, cosmetics, and cleaning supplies.

4.5.1 Technology and Commercial Readiness

Ethylene production via ethanol is practiced commercially at scales greater than 100,000 tonnes. Technology readiness is 9 and commercial readiness is 3.

4.5.2 UK Relevance

At its two world-scale bio-based ethanol plants, based on Teesside and the Humber, the UK has a bio-based ethanol capacity of 650,000 tonnes. This capacity represents an ethylene production potential of 375,000 tonnes.

Manufactured ethylene could either be consumed on site to produce a number of derivatives (e.g., polyethylene or ethylene oxide), or it could be transported via the UK's extensive ethylene pipeline

146 Braskem, Braskem expands its biopolymer production by 30% following an investment of US$ 87 million, https://www.braskem.com.br/europe/news-detail/braskem-expands-its-biopolymer-production-by-30-following-an-investment-of-us-87-million, [accessed 21 Dec. 2023].
147 Croda, Introducing our 100% bio-based ECO range of surfactants, https://www.crodahomecare.com/en-gb/sustainability/eco-range, [accessed 29 Jan 2024].

and used in an existing facility by adopting a mass balance approach for the production of bio-attributed products.

UK production of ethylene oxide ceased in 2010 with the closure of Dow Chemical's ethylene oxide production facility at Wilton.[148, 149]

Crop Energies, owner of UK ethanol producer Ensus, has taken a 50% investment in Dutch ethanol to ethylene technology developer Syclus BV.[150]

4.5.3 SWOT Analysis

Figure 23. SWOT analysis for production of ethylene from existing UK ethanol assets.

4.6 Methyl Methacrylate

Methyl methacrylic acid or methyl methacrylate (MMA) is primarily used in the production of polymethyl methacrylate (PMMA). PMMA is a transparent and rigid thermoplastic with a high resistance to UV light and weathering. PMMA's tensile strength, flexural strength, and transparency make it an ideal replacement for glass or polycarbonate. It is widely used in automotive parts (e.g., light fittings) and in the construction industry (e.g., skylights, roofing, and windowpanes).

Global production of MMA is in the region of 4 million tonnes.[151]

148 plastemart, Dow to shut UK ethylene oxide & glycol plant by Jan 2010 end, https://www.plastemart.com/news-plastics-information/dow-to-shut-uk-ethylene-oxide-glycol-plant-by-jan-2010-end/15782, [accessed 21 Dec. 2023].
149 Financial Times, Two chemicals plants in Teesside to close, July 8 2009, https://www.ft.com/content/672ea44c-6bdd-11de-9320-00144feabdc0, [accessed 21 Dec. 2023].
150 Crop Energies, CropEnergies acquires stake in Dutch bio-based chemicals start-up Syclus, https://www.cropenergies.com/en/press/details/cropenergies-erwirbt-anteile-am-niederlaendischen-start-up-fuer-biobasierte-chemikalien-syclus#:~:text=Ethylene%20made%20from%20renewable%20ethanol,for%20sustainable%20and%20recyclable%20plastics, [accessed 21 Dec. 2023].

151 Prismane, Consulting, Methyl Methacrylate Market Analysis – 2022, https://prismaneconsulting.com/blog-details/methyl-methacrylate-market-analysis-2022#:~:text=Methyl%20Methacrylate%20Market%20Overview,robust%20rate%20during%20the%20forecast, [accessed 21 Dec. 2023].

Mitsubishi Chemical Corporation and its subsidiary Mitsubishi Chemical Methacrylates are targeting the production of 'sustainable' MMA through three routes. Two approaches are based on the use of biomass, either by a switch of current chemical inputs from fossil to bio-based, or through the development of novel fermentation processes utilising fermentable sugars.

In 2022, the company announced the beginning of the design process for a new pilot plant to test the use of bio-based chemical inputs in the current MMA production process.[152]

4.6.1 Technology and Commercial Readiness

Routes to bio-based methyl methacrylate are currently in technical development at pilot or pre-pilot stage. Technology readiness is 4/5 and commercial readiness is 1.

4.6.2 UK Relevance

Mitsubishi Chemical UK is part of Mitsubishi Chemical Methacrylates within the Japanese chemicals company, Mitsubishi Chemical Group. Mitsubishi Chemical Methacrylates is world's largest producer of methacrylates.

Mitsubishi Chemical UK operated a 200,000 tonnes per year methacrylates plant in Billingham, Teesside. However, the company announced the formal closing of the site in April 2023.[153][154].

The company maintains a research group at Wilton, Teesside, comprising research scientists, laboratory analysts, engineers, safety roles, technical support and administration. Mitsubishi Chemical UK has a long standing and active research program in developing routes to bio-based MMA. This research program involves collaboration with several UK universities and includes a £4.3 million UK Research and Innovation 'Prosperity Partnership' collaboration with the University of Nottingham and the University of St Andrews to defossilise the production of acrylic-based materials.[155]

152 Mitsubishi Chemical Group, Design of Pilot Plant for MMA Monomers Using Plant-Derived Materials Has Begun, https://mcc-methacrylates.com/design-of-pilot-plant-for-mma-monomers-using-plant-derived-materials-has-begun/, , [accessed 21 Dec. 2023].
153 Mitsubishi Chemical Group, Notice on the Start of Consultation on Cessation of the Production of Methacrylates at the Cassel site, https://mcc-methacrylates.com/notice-on-the-start-of-consultation-on-cessation-of-the-production-of-methacrylates-atthe-cassel-site/, , [accessed 21 Dec. 2023].
154 mrchub, Mitsubishi confirms closure of its UK MMA plant, https://www.mrchub.com/news/407358-mitsubishi-confirms-closure-of-its-uk-mma-plant, [accessed 21 Dec. 2023].
155 Mitsubushi Chemical Group, Mitsubishi Chemical partners with the Universities of Nottingham and St Andrews to decarbonise the acrylic industry, https://mcc-methacrylates.com/mitsubishi-chemical-partners-with-the-universities-of-nottingham-and-st-andrews-to-decarbonise-the-acrylic-industry/, [accessed 21 Dec. 2023].

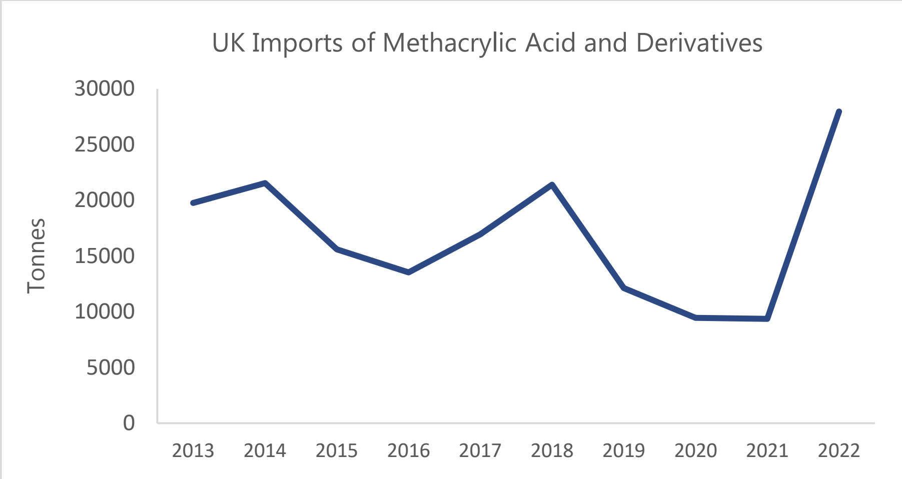

Figure 24. UK imports of Methacrylic acid, salts and esters.[156]

4.6.3 SWOT Analysis

Figure 25. SWOT analysis for UK production of methyl methacrylate from fermentable sugars

4.7 Methanol

Methanol is one of the seven primary chemicals underpinning the global petrochemical industry. Global methanol capacity is over 100 million tonnes with production estimated to be in the region of 70-80 million tonnes per year. The methanol market has been growing at a 3.6% CAGR[157] over the last 5 years.

Both methanol production and consumption are dominated by Asia-Pacific countries, with China and India among the countries with the largest consumption. China is responsible for around 60% of global production which is primarily derived from coal[56].

156 HM Revenue and Customs, https://www.uktradeinfo.com/trade-data/ [accessed 29 Jan 2024]
157 The Methanol Institute, https://www.methanol.org/, [accessed 29 Jan 2024]

Traditionally, formaldehyde has been the largest single end-use of methanol. It is used in the production of thermoset plastics such as PF (phenol-formaldehyde), UF (urea-formaldehyde) and MF (melamine-formaldehyde) resins, and used in applications from the construction of worktops and printed circuit board insulation, to use as adhesives in the production of plywood and hardboard.

Methanol is used to produce dimethyl terephthalate, a key intermediate in the production of polyethylene terephthalate (PET), and in the production of methyl methacrylate, an intermediate in the production of polymethylmethacrylate (PMMA), also known as Perspex. Other traditional chemical applications include the production of acetic acid, methylene chlorides, methylamines and methanethiol.

The concept of a methanol economy speaks to the new and emerging market opportunities for methanol. Methanol can be used to produce olefins such as ethylene and propylene, referred to as methanol-to-olefins (MTO) technology. MTO technology is not new, with development originating in the 1970's. However, commercial deployment has only taken hold since 2010. Developed by the Dalian Institute of Chemical Physics (DICP), the world's first commercial methanol to olefins unit (Shenhua's Baotou Coal to Olefins Plant) was commissioned in 2010 in northern China.[158] By 2019, 25 MTO plants had been commissioned in China. The demand for methanol from MTO production has grown from 16.2 million tonnes in 2015 to 24.6 million tonnes in 2019.

Methanol is also a leading candidate as a novel, low carbon marine fuel. In 2021, Maersk ordered the world's first methanol-enabled container vessel, following from a commitment to only ordering newbuilt vessels that can sail on green fuels. In 2023, the company ordered a further 5 methanol-enabled vessels and has stated that the global orderbook stands at more than 100 methanol-enabled vessels.[159]

4.7.1 Technology and Commercial Readiness

Methanol produced from carbon dioxide is being widely developed as an e-fuel for marine applications. Commercial production facilities are in planning and construction. Technology readiness is 9. However, commercial operation using biogenic carbon dioxide has not been demonstrated, therefore commercial readiness is 1.

4.7.2 UK Relevance

The UK operates a large trade deficit in methanol (Figure 26) and since 2001, has had no domestic production capacity. The UK has two large point sources of biogenic CO_2 emissions through its world scale ethanol production plants. The two plants, located within chemical manufacturing clusters on Teesside and the Humber, produce over 600,000 tonnes of CO_2 per year when operating at capacity. Additionally, the UK has a growing anaerobic digestion industry with the potential to supply significant quantities of CO_2. The UK has policies to stimulate the development of a low carbon hydrogen industry and business models to support industry deployment.

158 Chinese Academy of Sciences, World's First Commercial DMTO Process Succeeds in First Commissioning, https://english.cas.cn/newsroom/archive/research_archive/rp2010/201502/t20150217_141011.shtml, [accessed 21 Dec. 2023].
159 Maersk Press Release, 26 June 2023, https://www.maersk.com/news/articles/2023/06/26/maersk-orders-six-methanol-powered-vessels [accessed 23 Nov, 2023]

In 2022, the UK imported 622,000 tonnes of methanol with an import value of £224 million. INEOS acetyls have an annual demand of 365,000 tonnes of methanol which is used to produce acetic acid and downstream products such as ethyl acetate. Methanol is also a feedstock for the production chlorinated methanes. The INOVYN ChlorVinyls chloromethane complex in Runcorn has a 200,000 tonne per year chlorinated methanes capacity[160].

Ineos subsidiary INOVYN, is a member of the 'Power to Methanol' project, investigating options for sustainable methanol production at Antwerp, Belgium. The project has plans for an industrial-scale demonstration unit producing 8,000 tonnes of sustainable methanol per year.[161]

In 2021, Global Energy Group announced an agreement with Swiss-based integrated energy company, Proman, to explore the potential for a renewable power to methanol plant located at the Nigg Oil Terminal in the Highlands of Scotland, utilising local sources of carbon dioxide.[162]

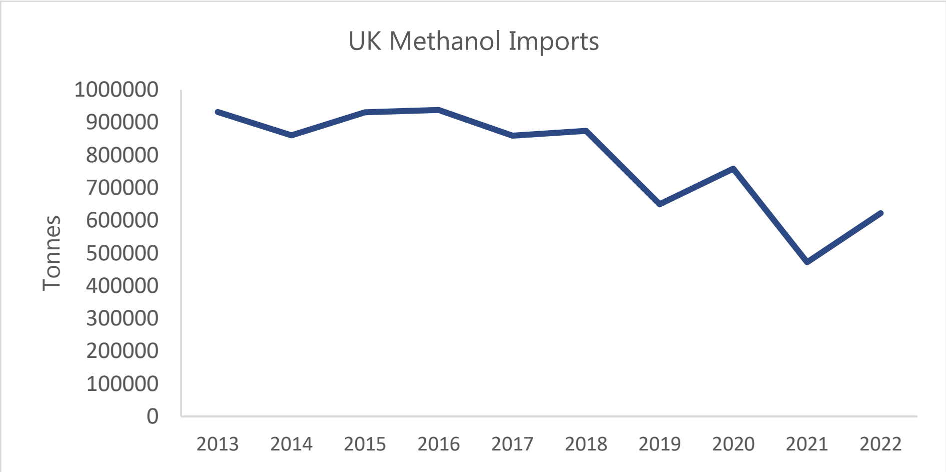

Figure 26. UK Methanol Imports.[163]

160 Environment Agency, Notice of variation and consolidation with introductory note, INOVYN ChlorVinyls Limited, Variation application number EPR/BS5428IP/V007, [accessed 28 Feb, 2024].
161 Ineos, INOVYN to play vital role in ambitious 'power to methanol' project to produce sustainable methanol and reduce CO2 in Antwerp, https://www.ineos.com/news/shared-news/inovyn-to-play-vital-role-in-ambitious-power-to-methanol-project-to-produce-sustainable-methanol-and-reduce-co2-in-antwerp/, [accessed 21 Dec, 2023].
162 Renewable Energy Group, Global Energy Group and Proman to develop a renewable power to methanol plant at the Nigg Oil Terminal, https://gegroup.com/latest/global-energy-group-and-proman-to-develop-a-renewable-power-to-methanol-plant-at-the-nigg-oil-terminal, [accessed 21 Dec, 2023].
163 HM Revenue and Customs https://www.uktradeinfo.com/trade-data/, [accessed 21 Dec, 2023].

4.7.3 SWOT Analysis

Figure 27. SWOT analysis for UK methanol production from carbon dioxide

5 Distributed Bio-manufactured Chemicals

5.1 Introduction

Distributed manufacturing of bio-based chemicals in biofactories considers smaller capacity facilities in comparison to biorefineries. The facilities may be scaled to the availability of feedstocks, the optimal technoeconomic design, or to market requirements.

5.2 Butanol with Acetone and Ethanol (ABE)

N-butanol is primarily used in the production of butyl acrylate and butyl acetate. It is also used as a solvent and as an ingredient in various formulations such as in cosmetics and as a starting material to produce other chemicals. N-Butanol is widely used in the coatings industry where it is used as a diluent in cellulose nitrate lacquers as it improves their flow, gloss and resistance to blushing. It is also used as a solvent for acid-curable lacquers, and in baking finishes derived from urea, melamine, or phenolic resins, where it is mainly used together with glycol ethers or ethanol.

Other uses include as a solvent for dyes in printing inks, as an additive in polishes, cleaners and stain removers, as a swelling agent for textiles, and as an extractant in the production of drugs.

The production of butanol, along with acetone and ethanol, via fermentation (named ABE fermentation) has a long history, dating back to its development in the UK in the early 20th century[164]. Although widely commercialised, fermentation-based production of butanol declined in the second half of the 20th century due to its unfavourable economics when compared to petrochemical production.

164 Moon et, al. One hundred year of clostridial butanol fermentation, https://academic.oup.com/femsle/article/363/3/fnw001/2594553, [accessed 30 Jan, 2023].

5.2.1`Technology and Commercial Readiness

Butanol via ABE fermentation is an historic technology, although not currently commercially practiced. Production is being demonstrated in the UK and commercial production facilities are being planned. Technology readiness is 9 and commercial readiness is 2.

5.2.2 UK Relevance

Scottish bio-based chemical company, Celtic Renewables, have been developing their ABE fermentation process to convert whisky production residues to butanol, ethanol and acetone since 2008. The company is now demonstrating their process at a state-of-the-art commercial processing plant at Caledon Green, in Grangemouth Scotland.[165] The plant is expected to produce nearly one million litres of bio-based chemicals (ABE) annually.[166] The company has plans to site ABE production facilities alongside whisky production and take advantage of available sources of grade-B reject potatoes.[167]

The UK has no domestic production of butanol and imports over 10,000 tonnes per year. UK imports of acetone pre the COVID-19 pandemic were over 100,000 tonnes per year.

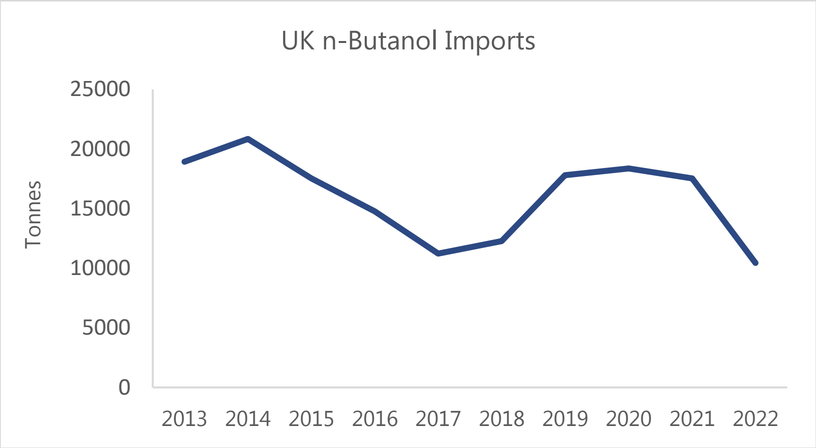

Figure 28. UK imports of n-butanol.[168]

165 Celtic Renewables, Production facility, https://www.celtic-renewables.com/production-facility/, [accessed 21 Dec, 2023].
166 Scottish Development International, Celtic Renewables is turning whisky by-products into a global renewables business, https://www.sdi.co.uk/news/celtic-renewables-is-turning-whisky-by-products-into-a-global-renewables-business, [accessed 12 Jan, 2024].
167 Celtic Renewables, Private communication, 2023.
168 Source HM Revenue and Customs https://www.uktradeinfo.com/trade-data/, [accessed 21 Dec, 2023].

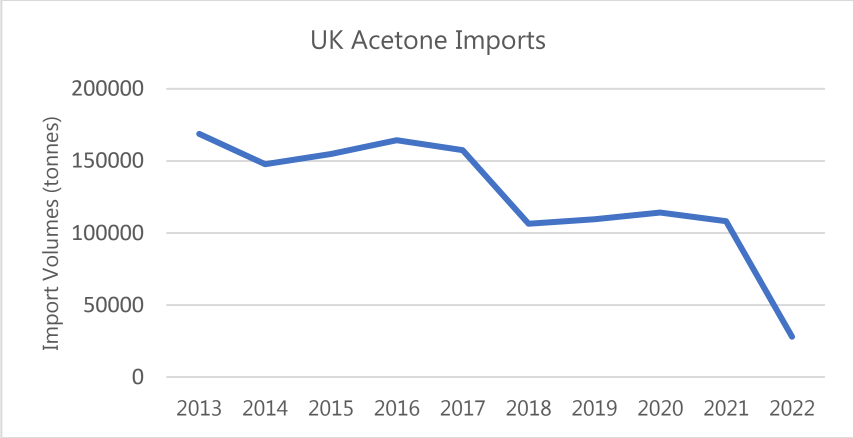

Figure 29. UK imports of acetone.[169]

5.2.3 SWOT Analysis

Figure 30. SWOT analysis of UK production of butanol and acetone via an ABE fermentation process.

5.3 Biosurfactants

Surfactants, (surface-active agents), are compounds that lower the surface tension between two liquids, or between a liquid and a solid. They are widely used in personal care products (e.g., cosmetics and shampoos etc.), homecare products (e.g., detergents and cleaning products), as dispersants in paint, ink formulations, in agricultural applications (e.g., pesticide formulations), and in the food industry as emulsifiers, stabilizers, and dispersants.

Types of surfactants, include anionic, cationic, nonionic, and amphoteric surfactants. They are typically produced synthetically using a fossil chemical and vegetable oil raw materials.

169 Source HM Revenue and Customs https://www.uktradeinfo.com/trade-data/, [accessed 21 Dec, 2023].

Biosurfactants are produced through microbial fermentation processes. Types of biosurfactant include rhamnolipids, sophorolipids, surfactin and mannosylerythritol lipids.

Biosurfactants are mild on the skin and have a low toxicological and ecotoxicological profiles. Biosurfactant properties make them suitable for use in a broad range of applications including laundry detergents, hard surface cleaners, vehicle care, and cleaning formulations for the food and beverage industry.

German chemical producer, Evonik, offers both sophorolipids and rhamnolipid surfactants and has built a new production plant in Slovakia, which began producing product in January 2024.[170, 171]

5.3.1 Technology and Commercial Readiness

Biosurfactant production is being demonstrated in the UK and commercial production facilities are being planned. Technology readiness is 9 and commercial readiness is 2.

5.3.2 UK Relevance

UK based biosurfactant company, Holiferm, has developed a novel process technology to produce sophorolipids in a continuous manufacturing process. In 2023, the company opened its one thousand tonne scale commercial demonstration plant on the Wirral, Merseyside. Holiferm has secured finance to increase capacity to 3,500 tonnes per annum before further scaling up to 15,000 tonnes per annum capacity.[172]

The UK has a large and vibrant personal care sector providing a significant off-take opportunity for a biosurfactant manufacturer.

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170 Evonik, Evonik enters new era of cleaning with launch of REWOFERM® RL 100 biosurfactant, https://household-care.evonik.com/en/news/press-releases/evonik-enters-new-era-of-cleaning-with-launch-of-rewoferm-rl-100-biosurfactant-170823.html, [accessed 21 Dec. 2023].
171 Evonik, Evonik manufactures first product from world's first industrial-scale rhamnolipid biosurfactant plant, https://corporate.evonik.com/en/investor-relations/evonik-manufactures-first-product-from-worlds-first-industrial-scale-rhamnolipid-biosurfactant-plant-233304.html, [accessed 19 Mar. 2024].
172 Holiferm, Holiferm secures £18.5 million to scale up to 15kta production capacity from Rhapsody Venture Partners and Clean Growth Fund, https://holiferm.com/holiferm-news/holiferm-secures-18-5-million-to-scale-up-to-15kta-production-capacity-from-rhapsody-venture-partners-and-clean-growth-fund/, [accessed 21 Dec. 2023].

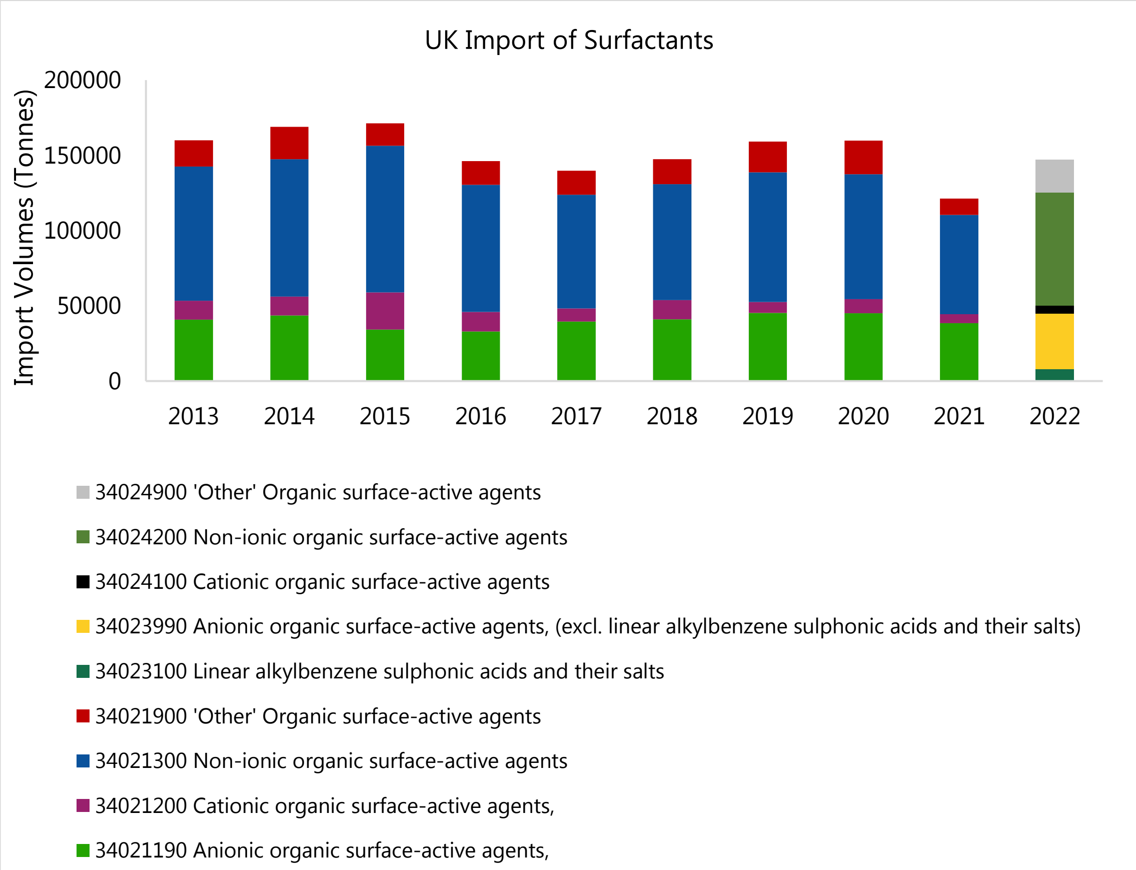

Figure 31. UK imports of surfactants (by Harmonized System (HS) Code).[173]

5.3.3 SWOT Analysis

Figure 32. SWOT analysis of UK production of biosurfactants.

173 HM Revenue and Customs, https://www.uktradeinfo.com/trade-data/, [accessed 21 Dec. 2023].

5.4 Furandicarboxylic Acid

Furandicarboxylic acid (FDCA) can be used for a range of chemical (e.g., surfactants), and polymer applications (e.g., polyesters, polyamides and polyurethanes) and is considered an attractive replacement of fossil-derived terephthalic acid.

FDCA has received the most attention in regard to the production of polyethylene 2,5-furandicarboxylate, also known as polyethylene furanoate (PEF). PEF is chemically similar to the widely used polyester, polyethylene terephthalate (PET), but when produced in conjunction with bio-based ethylene glycol, provides a 100% bio-based polymer. PEF offers some superior properties to PET which makes it an interesting packaging polymer e.g., for use in carbonated drinks bottles (i.e., increased CO_2 barrier properties) and in oxygen-sensitive food and beverage packaging (i.e., increased O_2 barrier properties). These attributes result in longer shelf lives for perishable products which then drives interest in this polymer from food and beverage companies.

There is no established market or supply of polyethylene furanoate at present. This is largely a result of its principal monomer, FDCA, not being widely available as a precursor for commercial scale PEF production.

Several companies are currently developing routes to FDCA production, these include Dutch company Avantium[174]; a collaboration between DuPont and ADM[175]; Finnish forestry products company, Stora Enso[176]; and Italian bio-based polymer producer, Novamont[177].

5.4.1 Technology and Commercial Readiness

Routes to bio-based FDCA are being developed by multiple companies. Technology development is beyond pilot, and demonstration plants are in construction. Technology readiness is 8 and commercial readiness is 1.

5.4.2 UK Relevance

In 2019, Alpek Polyester acquired Lotte Chemical UK's 350,000 tonne per year polyethylene terephthalate (PET) facility at Wilton.[178] The PET chips produced at the plant serve around 75% of the UK market, with the polymer mainly used in bottling carbonated soft drinks, water and food

174 Avantium, Avantium celebrates the First Piling Ceremony for its FDCA Flagship Plant, https://www.avantium.com/wp-content/uploads/2022/04/20220420-Avantium-celebrates-First-Piling-Ceremony-of-its-FDCA-Flagship-Plant_final.pdf, [accessed 02 Jan. 2024].
175 ADM, Industry Leaders DuPont, Archer Daniels Midland Company Win Platts Global Energy Breakthrough Solution of the Year Award https://www.adm.com/en-us/news/news-releases/industry-leaders-dupont-archer-daniels-midland-company-win-platts-global-energy-breakthrough-solution-of-the-year-award/, [accessed 02 Jan. 2024].
176 Stora Enso, FuraCore® FDCA as a bio-based specialty chemical, https://www.storaenso.com/en/products/bio-based-materials/furacore-fdca/furacore-fdca-for-other-applications, [accessed 02 Jan. 2024].
177 Novamont, Intesa Sanpaolo and Novamont : 20-million Euro circular load agreement for two innovative projects, https://www.novamont.com/eng/read-press-release/intesa-sanpaolo-and-novamont-20-million-euro-circular-loan-agreement-for-two-innovative-projects/, [accessed 02 Jan. 2024].
178 Alpek Polyester, Alpek signs agreement to acquire PET facility from Lotte Chemical, https://www.alpekpolyester.com/wp-content/uploads/2022/11/Alpek-Lotte-Chemical-UK-Acquisition.pdf, [accessed 02 Jan. 2024].

packaging.[179] Lotte Chemical UK also operated a 500,000 tonne capacity purified terephthalic acid plant at the Wilton site. However, this plant was closed in early 2014.[180]

FDCA is seen as a potential replacement for terephthalic acid. Until recently, the UK imported over 40,000 tonnes of terephthalic acid and its salts annually (Figure 33), although trade data indicates imports of terephthalic acid to be zero for years 2021-2022, industry sources confirmed a current import volume of over 100,000 tonnes[181]. The UK currently has no domestic production of terephthalic acid.

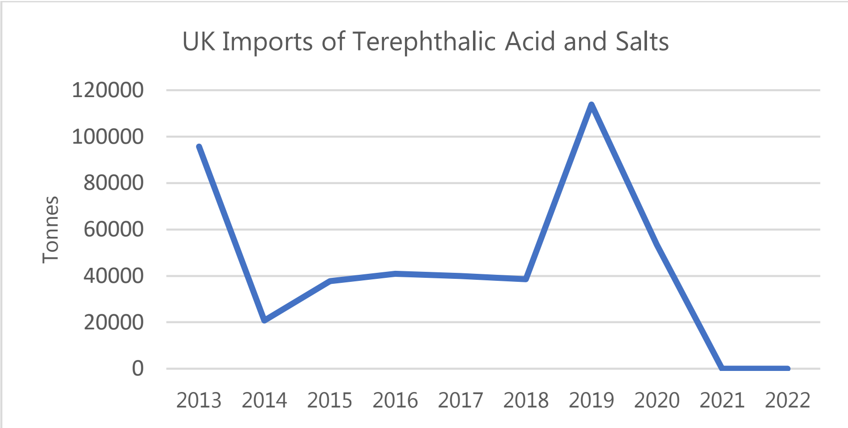

Figure 33. UK Imports of Terephthalic acid and salts.[182]

Alpek Polyester have expressed an interest in FDCA development as a potential alternative to terephthalic acid.[183]

5.4.3 SWOT Analysis

Figure 34. SWOT analysis of UK production of furandicarboxylic acid using chemical conversion of sugar.

179 Nepic, Alpek Polyester UK Company Profile, https://www.nepic.co.uk/company-profile/2020/, [accessed 02 Jan. 2024].
180 BBC News, Lotte Chemical plant in Wilton closes with 70 job losses, https://www.bbc.co.uk/news/uk-england-tees-25213602, [accessed 02 Jan. 2024].
181 Private communication in confidence, Alpek Polyester, 2024.
182 Source HM Revenue and Customs https://www.uktradeinfo.com/trade-data/, [accessed 02 Jan. 2024].
183 Alpek Polyester, Private Communication, 2023.

5.5 Butanediol

Global 1,4 butanediol (BDO) production is in the region of 2.5 million tonnes[184]. Major uses include the production of tetrahydrofuran (THF) and γ-butyrolactone (GBL), as a plasticiser in resins, and as an industrial solvent. Tetrahydrofuran (THF) production represents the largest user segment. THF is widely used as a solvent and in the production of polytetramethylene ether glycol (PTMEG). PTMEG is an important raw material to produce polyurethane (PU) (e.g., PU fibres, PU elastomers, synthesized leathers, paint additives, adhesives and sealants), polyesters and polyamides. BDO is also an important precursor for the production of polyTHF, an essential starting material for elastic spandex and elastane fibres that are used for a wide range of textiles.

1,4-butanediol is also a monomer in the production of polybutylene adipate terephthalate and polybutylene succinate. Both polymers are biodegradable and have applications in the production of compostable packaging and in biodegradable agricultural mulch films.

American industrial biotechnology company, Genomatica, offers its Geno BDO™ process technology under license. Licence deals have been agreed with Novamont, BASF and Quore. Novamont opened the world's first bio-based 1,4-butanediol plant in 2016, using Genomatica technology.

5.5.1 Technology and Commercial Readiness

A technology licence for the production of bio-based 1,4-butanediol is available. Commercial production is in operation. Technology readiness is 9 and commercial readiness is 3.

5.5.2 UK Relevance

Industrial biotechnology provides an increasingly attractive process route to 1,4-butanediol. The UK's investments and expertise in synthetic biology means that it is well placed to develop and deploy new production processes.

1,4-butandiol is one of only a few chemicals where trade data is provided specifically for the bio-based chemical. The UK import of 1,4-butanediol is limited. Around 1,000 tonnes have been imported annually since 2016.

184 Genomatica, Our products, https://www.genomatica.com/products/, [accessed 02 Jan. 2024].

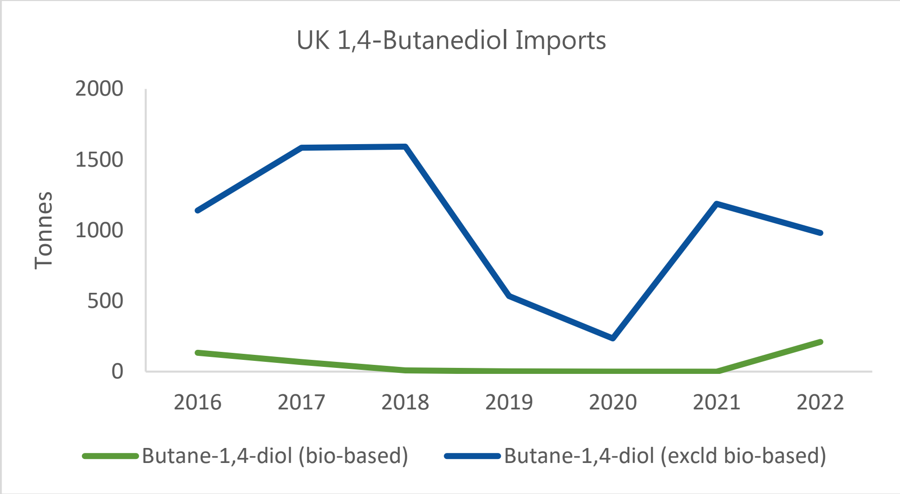

Figure 35. UK imports of bio-based 1,4-butanediol.[185]

5.5.3 SWOT Analysis

Figure 36. SWOT analysis of UK production of 1,4-butanediol from fermentable sugars.

5.6 Succinic Acid

Succinic acid is a small volume commodity product. The global market was estimated at 70,000 tonnes in 2023.[186] It is widely used as an acidity regulator and flavouring agent in the food and beverage industry. It is also used as an excipient in the production of pharmaceuticals. Other uses include as an automotive coolant, corrosion inhibitor, and in de-icers. Succinic acid is a monomer in the production of the biodegradable polymer, polybutylene succinate.

In addition to being a drop-in replacement for fossil-based succinic acid, it can also replace fossil-based adipic acid.

185 Source HM Revenue and Customs https://www.uktradeinfo.com/trade-data/, [accessed 02 Jan. 2024].
186 Chem Analyst, Succinic Acid Market Analysis, https://www.chemanalyst.com/industry-report/succinic-acid-market-2899, [accessed 02 Jan. 2024].

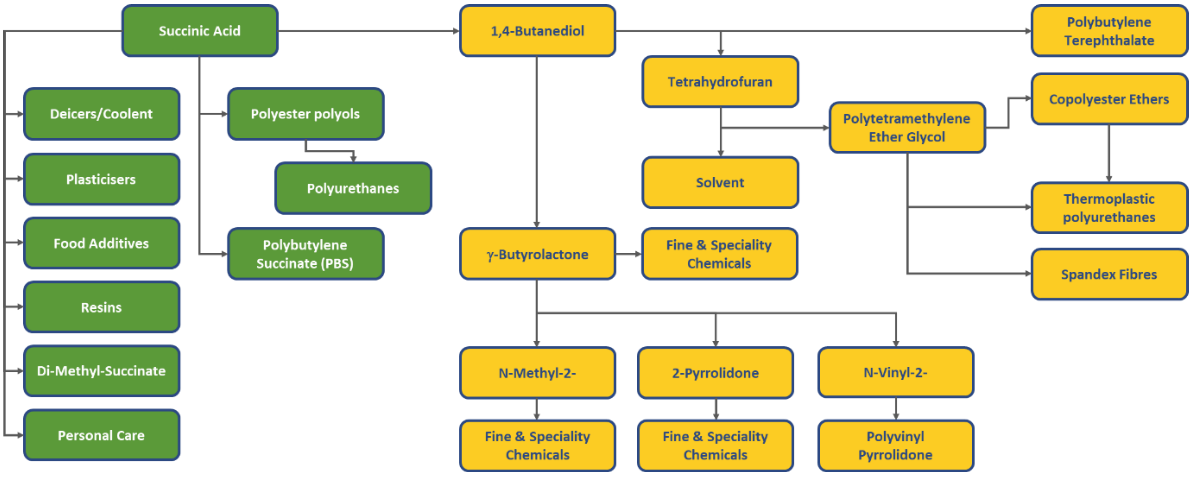

Figure 37. Succinic acid and 1,4-butanediol value chains.

5.6.1 Technology and Commercial Readiness

Multiple fermentation processes for the production of succinic acid have been demonstrated and commercial plants have been constructed. However, commercial plant viability has not yet been demonstrated. Technology readiness is 9 and commercial readiness is 2.

5.6.2 UK Relevance

Seqens (incorporating Chemoxy) is one of Europe's largest independent contract manufacturers.[187] Seqens produces Estasol®, a general-purpose solvent with a low vapour pressure and a broad range of applications. Estasol® is a mixture of refined dimethyl esters of adipic, glutaric and succinic acids.[188] Estasol® has applications in wood coatings, floor coatings, commercial graffiti removal, paint strippers, textile lubricants, and in polyurethane clean-up. Chemoxy has collaborated in UK research and development projects looking to develop routes to bio-based succinic acid.[189]

Succinic acid is one of only a few chemicals where trade data is provided specifically for the bio-based chemical. The UK trade in bio-based succinic acid is limited, less than 100 tonnes are generally imported or exported annually. However, there is the possibility to the increase the use of succinic acid in compostable polymers, and if production costs can be reduced, the potential market is significant. Unfortunately, succinic acid trade data is aggregated with several other acyclic polycarboxylic acids and derivatives, and therefore, import volumes are not available.

187 Chemoxy, Company overview, http://www.chemoxy.com/about-2/overview/, [accessed 02 Jan. 2024].
188 Chemoxy, Estasol ®, http://www.chemoxy.com/products-and-applications/products/coalescents/estasol/, [accessed 02 Jan. 2024].
189 CPI, University of Manchester improve biodiesel manufacture, https://www.uk-cpi.com/news/cpi-university-manchester-work-improve-economic-proposition-uk-biodiesel-manufacture/, [accessed 02 Jan. 2024].

5.6.3 SWOT Analysis

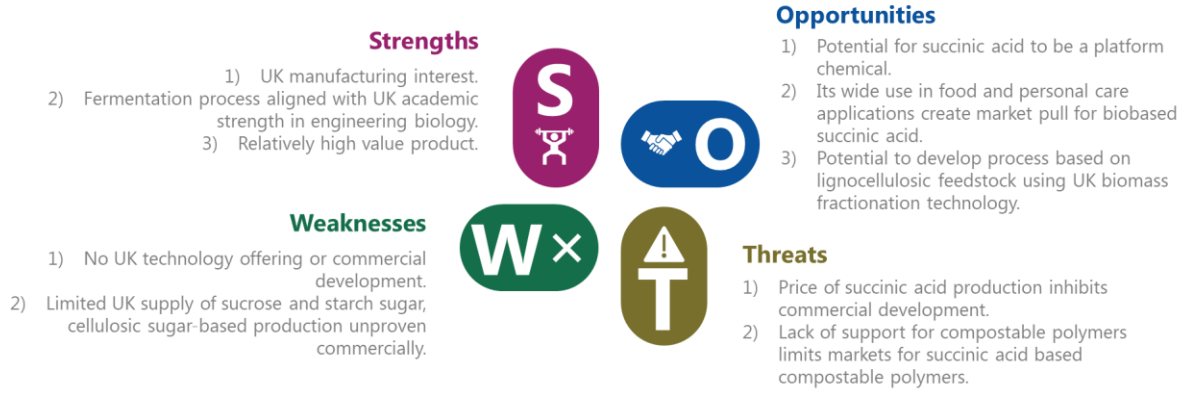

Figure 38. SWOT analysis of the production of the UK production of succinic acid from fermentable sugars.

5.7 Dihydrolevoglucosenone (Novel Solvents)

The bio-based solvent Cyrene™, has been developed by the Norwegian headquartered, Circa Group. Cyrene is produced from levoglucosenone which in turn is produced from lignocellulosic biomass using the company's Furacell™ process.

Cyrene® is a non-toxic solvent which belongs to the 1,000,000 tonne plus per annum solvent family of dipolar aprotic solvents. Cyrene® has the potential to replace traditional dipolar aprotic solvents, such as NMP and DMF, in a range of markets.

Dipolar aprotic solvents are used in large quantities around the world, but they face mounting regulatory pressures due to issues associated with their apparent toxicity, to both humans and the natural environment. NMP and DMF are two fossil-derived, dipolar aprotic solvents, both classified as 'Substances of Very High Concern' (SVHC) under authority of the EU's 'Registration, Evaluation, Authorisation and Restriction of Chemicals' (REACH) Regulation. SVHC labelling is recognised as the first step before the placing of harsher restrictions on the chemicals in question. It follows that both NMP and DMF are likely to become more heavily regulated in the future.

As part of the European BBI JU funded ReSolute project, Circa are building a first-of-a-kind 1,000 tonne per annum plant in France.[190] In October 2023, Circa signed a Memorandum of Understanding with Thailand's National Power Supply Public Company Limited (NPS) for the evaluation of sites for Circa's next stage plant, with an approximate capacity for the production of 12,000 tonnes of green solvent Cyrene™ and platform chemical levoglucosenone.[191]

190 Resolute Project, About the project, https://www.resolute-project.eu/, [accessed 02 Jan. 2024].
191 Circa, Circa And NPS Sign Memorandum of Understanding, https://circa-group.com/news/circa-and-nps-sign-memorandum-of-understanding/, [accessed 02 Jan. 2024].

5.7.1 Technology and Commercial Readiness

The production of dihydrolevoglucosenone is currently being demonstrated and commercial production is in planning. Technology readiness is 8 and commercial readiness is 1.

5.7.2 UK Relevance

Circa has close ties with the University of York, with significant applications development taking place at the University. Circa have now established the Circa Renewable Chemistry Institute within the University of York's Green Chemistry Centre of Excellence.[192] The Institute aims to advance and promote the development and commercialization of renewable chemistry, processes and products that enable the chemical industry to transition to commercially viable, sustainable, and environmentally responsible bio-based products at an industrial scale. This aim incorporates enabling the uptake of Circa's innovative bio-based chemicals through specific application development and process support.

Circa aims to scale production to a plant capacity of 12,000 tonnes, and then eventually, 80,000 tonnes. Circa's commercial plans are currently focused on forestry residue feedstocks, but their Furacell™ process can be applied to the processing of the biogenic fractions of municipal solid wastes or cereal straws. Circa's process could take advantage of the large volumes of forest biomass (i.e., biomass pellets) currently imported by UK-based biomass electricity producers. The predominate output of the Cyrene™ production process is biochar, which accounts for >90% of the process output. This biochar output could be used as a biofuel, effectively returning the bulk of the biomass used back to the bioenergy value chain.

5.7.3 SWOT Analysis

Figure 39. SWOT analysis of UK production of bio-based solvent dihydrolevoglucosenone (Cyrene™).

192 Circa, Circa Renewable Chemistry Institute, https://www.york.ac.uk/chemistry/research/green/industry/crci/, [accessed 02 Jan. 2024].

6 Opportunity Rating

Each of the 15 target chemicals (with their production pathways) were rated red, amber or green (RAG), against three selection criteria as shown in Table 19.

Chemical Target	Credible /Achievable *(TRL & CRI)*	Meaningful *(potential impact)*	Plausible/Realistic *(relative potential)*
Lactic Acid as PLA (from biogenic MSW)	TRL 8/CRI 1	Production potential >100,000tonnes	Strong interest from potential UK producer
Monoethylene glycol (from cellulosic sugar)	TRL 9/CRI 2	Production potential >100,000tonnes	Interest from UK value chain.
Ethyl Acetate (from ethanol)	TRL 9/CRI 2	Production potential >100,000tonnes	Strong interest from non-UK company with UK assets
Ethylene (from ethanol)	TRL 9/CRI 3	Production potential >100,000tonnes	Interest from non-UK company with UK assets
Methyl methacrylate (from starch/sucrose sugar)	TRL 4-5/CRI 1	Production potential >100,000tonnes	Supported by multi-national with global view
Methanol (from CO_2)	TRL 9/CRI 1	Production potential >100,000tonnes	Interest from potential UK producer
Butanol/Acetone/Ethanol (from agri-food by-products)	TRL 9/CRI 2	Production potential >10,000tonnes	UK technology and producer
Biosurfactant (from starch/sucrose)	TRL 9/CRI 2	Production potential >10,000tonnes	UK technology and producer
Furandicarboxylic acid (from cellulosic sugar)	TRL 7-8/CRI 1	Production potential >10,000tonnes	Interest from value chain.
1,4-Butanediol (from starch/sucrose)	TRL 9/CRI 3	Production potential >10,000tonnes	Interest from value chain.
Succinic acid (from starch/sucrose)	TRL9/CRI 2	Production potential >10,000tonnes	Interest from value chain.
Dihydrolevoglucosenone, Cyrene™ (from lignocellulose)	TRL 8/CRI 1	Production potential >10,000tonnes	Interest from non-UK company with UK research interest and potential interest in UK production.
Ethylene/Propylene (from bio-based propane)	TRL9/CRI 3	Limited	UK interest in propane could not be determined.
Acetic acid (from biomethane)	TRL 9/CRI 1	Production potential >100,000tonnes	UK based production of feedstock and product
Ethylene (from bio-based naphtha)	TRL9/CRI 3	The switch from liquid to gas crackers means the UK no longer has the capability to process liquid naphtha feedstock	

Table 19. RAG rating of target chemicals for UK production.

7 Feedstock Availabilities and Requirements

In 2022, 66% of biomass feedstocks used in bioenergy supply (heat, electricity, and transport) were from domestic sources. The potential supply of biomass for UK bioenergy use is has been extensively studied and is discussed in detail within the 2023 UK Biomass Strategy.[193]

For the purposes of this study biomass types can be grouped according to origin, physicochemical characteristics and application.

- Arable crops as a source of starch and sucrose for fermentation and chemical conversion e.g., wheat and sugar beet.
- Biomass crops as a source of cellulosic sugars for fermentation and chemical conversion e.g., miscanthus and short rotation coppice.
- Agricultural and forestry residues, as a source of cellulosic sugars for fermentation and chemical conversion e.g., straws, forestry harvesting residues, sawmill co-products, agricultural process residues.
- Food and agricultural wastes as inputs to anaerobic digestion and the production of biomethane e.g., food waste, sewage sludge and animal slurries.

Other biomass sources not separately considered in this study include oils and fats e.g., used cooking oil, tallow, microalgal oils, and fats oils and greases (FOG) for example.

Modelling the future availability of biomass supply is challenging and inherently uncertain. Biomass supply is determined by a range of technoeconomic, market demand and political/policy factors which can stimulate supply, create market competition or restrict supply based on sustainability considerations.

The modelling underpinning the UK Biomass Strategy suggests that the total potential of sustainable biomass estimated to be available for UK use is highly uncertain. Scenario modelling resulted in estimates of availability with values of 550-750 PJ in 2025, and 500-1,000 PJ in 2050.

This variation in potential results from assumptions based on the availability of sustainable biomass imported into the UK. The availability of domestic biomass remained relatively stable, in the region of 370-390 PJ in 2050, across restricted and ambitious supply scenarios.

A key process intermediate for the production of bio-based chemicals is glucose, either as a fermentation substrate or for chemical processing. A range of biomass feedstocks are considered as important sources of glucose (Table 20). The potential availability of glucose is assessed to be in the order of 9 million tonnes in 2050.

A key uncertainty in the future volume of available biomass lies in the development and expansion of biomass crop cultivation. Supportive Government policy coupled with yield improvements could

193 DESNZ, Biomass Strategy, 2023, https://assets.publishing.service.gov.uk/media/64dc8d3960d123000d32c602/biomass-strategy-2023.pdf, [accessed 09 Jan. 2024].

increase the availability of biomass crops by around 11 million tonnes, thus, adding an additional 6 million tonnes of sugar availability.[194]

Feedstock	Biomass availability (million odt)	Glucose availability (million odt)	Source
Field residues (e.g., straw)	0.9	0.3	DESNZ Biomass Resource Model)
Forest products and residues	6.1	2.7	DESNZ Biomass Resource Model)
Residual biogenic waste	2.6	1.2	DESNZ Biomass Resource Model
Biomass crops	2.0	0.9	DESNZ Biomass Resource Model)
Agricultural process residues	1.3	0.4	DESNZ Biomass Resource Model)
Sub-total	**15**	**7**	
Cereal grain	2.2	1.7	Estimate based on established UK bioethanol capacity
Total	**17.2**	**8.7**	

Table 20. UK biomass and glucose availability by type. (Source DESNZ Biomass Resource Model)

It should be noted that the processing of lignocellulosic biomass to obtain glucose also results in the production of lignin and hemicellulose which can be processed in a multitude of ways to produce fuel products or as inputs for chemical production.[195, 196]

7.1 Arable Crops

Food and feed crops are used in a range of bioenergy applications e.g., the use of wheat for bioethanol production and maize as a feedstock for anaerobic digestion and biogas production. The UK has a bio-based ethanol capacity of 650,000 tonnes requiring around 2.2 million tonnes of wheat. Anaerobic digestion primarily uses animal-derived wastes (such as slurries, manures and poultry litter), food wastes and industrial organic wastes as feedstocks. However, maize is also commonly used as a feedstock.

The government's policy on the use of food and feed crops is to carefully balance the environmental benefits of their use as biofuel feedstocks with concerns over direct competition with food markets, indirectly distorting existing markets, and potential issues with land biodiversity or soil carbon. For example, the Government's Renewable Transport Fuel Obligation (RTFO) and Green Gas Support Scheme (GGSS) includes limits on the use of arable (food and feed) crops in biofuel generation.

194 Ricardo AEA, DESNZ UK Biomass Availability Model, [accessed 09 Jan. 2024].
195 Ajao et al, Hemicellulose based integrated forest biorefineries: Implementation strategies, https://www.sciencedirect.com/science/article/abs/pii/S0926669018308872, [accessed 09 Jan. 2024].
196 NNFCC, Lignin valorisation, Opportunities from cellulosic sugar production, https://theicct.org/publication/lignin-valorisation-opportunities-from-cellulosic-sugar-production/, [accessed 22 Jan. 2024]

For the purposes of this report, it is not anticipated that bio-based chemical production would result in an increasing industry use of arable crops above current biofuel use, but rather from a transition of use from biofuel to bio-based chemicals. Therefore, the maximum potential is regarded as being the 2.2 million tonnes of wheat. However, studies have been performed to assess the potential to increase the UK supply of fermentable sugar from arable crops, specifically sugar beet.[197, 198] Chemical production from sugar beet, or sugar beet process residues, is considered possible, with current UK beet ethanol production capacity at around 75 million litres of bioethanol per year[199].

7.2 Biomethane Feedstock

Biomethane is obtained from the upgrading of biogas produced as a product of anaerobic digestion (AD). Biomethane can be injected into the gas grid, where it directly displaces fossil derived natural gas.

Preferred feedstocks for AD are animal-derived wastes (such as slurries, manures and poultry litter), food wastes and industrial organic wastes. AD acts as an important waste treatment process by reducing GHG emissions e.g., the treatment of food waste through AD delivers significant GHG savings over sending food waste to landfill.

In 2022, 21 TWh of biogas were used for electricity production and 6.2 TWh of biomethane was injected into the UK gas grid.[200] Biomethane is considered an important decarbonisation strategy and the volumes produced and injected into the gas grid are expected to increase considerably over the next 10 years. The Climate Change Committee estimates that production capacity will reach 20 TWh in 2030 (with no growth to 2050).[201] However, proponents of biomethane point to a potential supply of up to 55-76 TWh in the future.[202]

7.3 Lignocellulosic Biomass Feedstock

Lignocellulosic biomass is a flexible chemical feedstock. To varying degrees of efficiency and cost, this biomass can be thermally processed through gasification or pyrolysis e.g., gasification followed by

197 NNFCC, Opportunities for re-establishing sugar beet production and processing in Scotland, https://www.nnfcc.co.uk/publications/report-sugar-beet-scotland, [accessed 12 Jan. 2024].
198 IBioIC, Sugar Beet: A Just Transition for the Chemicals Sector and a Net Zero Solution for Manufacturing, https://www.ibioic.com/publications-database/sugar-beet-a-just-transition-for-the-chemicals-sector-and-a-net-zero-solution-for-manufacturing, [accessed 12 Jan. 2024].
199 British Sugar, Bioethanol, https://www.britishsugar.co.uk/about-sugar/co-products, [accessed 12 Jan. 2024].
200 Digest of UK Energy Statistics (DUKES): renewable sources of energy, 2023, https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes, [accessed 10 Jan. 2024].
201 The Climate Change Committee, Technical Note: Biomethane 2016, https://www.theccc.org.uk/wp-content/uploads/2016/12/2016-PR-Biomethane-Technical-Note.pdf, [accessed 12 Jan. 2024].
202 ADBA, Biomethane: The Pathway to 2030, https://adbioresources.org/report-biomethane-the-pathway-to-2030/, [accessed 09 Jan. 2024].

Fisher-Tropsch synthesis[203] of hydrocarbons or to produce methanol;[204] or fractionated to provide cellulose, hemicellulose and lignin as feedstocks for further chemical processing.[205, 206]

Lignocellulosic biomass takes many forms. It includes biomass crops (such as miscanthus and short rotation willow), primary products, harvest residues, and processing by-products from the forestry industry (including small roundwood, short rotation forestry and sawmill residues), and agricultural field residues (e.g., straws) and agricultural processing residues (e.g., cereal husks).

The UK Biomass Availability Model[208] suggests that around 10 million tonnes of lignocellulosic biomass is available for use.

The potential to expand this volume of feedstock is largely based on assumptions around the land available and cultivation yields of biomass crops (e.g., miscanthus and short rotation coppice) and short rotation forestry. As stated in the Biomass Strategy, 'it is likely that the UK will grow more biomass here in the future, but domestic biomass cultivation and deployment should not compromise the government's commitment to broadly maintain current levels of food production, or ability to meet our legally binding Environment Act 2021 targets'.[207]

More optimistic scenarios around lignocellulosic biomass suggest that availability could reach up to 20 million tonnes by 2050.[208]

7.4 Residual Biogenic Waste

Residual waste is typically defined as residual "municipal waste" i.e., household waste, and waste from other sources, which is similar in nature and composition to household waste that cannot be prevented, reused or recycled. Residual waste contains a significant proportion of biogenic material, like food, paper/card and wood.

Residual waste is typically treated in three ways: recovery of energy to produce electricity and heat through domestic Energy from Waste (EfW) plants; production of refuse derived fuel (RDF) for export and energy recovery overseas; or disposal to landfill. However, residual waste could also be processed into transport fuels,[209] or used as a chemical feedstock[210].

Although improved recycling rates and the introduction of legal requirements for separate food waste collections will reduce both the volumes of residual waste and its biogenic content, it is still

203 ETIP Bioenergy, Biomass to Liquids (BTL) vis Fisher-Tropsch A brief review, www.etipbioenergy.eu, [accessed 10 Jan. 2024].
204 ETIP Bioenergy, Methanol from Biomass Fact Sheet, www.etipbioenergy.eu, [accessed 10 Jan. 2024].
205 BBNet, Pre-treatments to enhance the enzymatic saccharification of lignocellulose: technological and economic aspects, https://www.bbnet-nibb.co.uk/wp-content/uploads/2021/02/BBNet-Pretreatment-Tech-Review-Feb2021-.pdf, [accessed 09 Jan. 2024].
206 Sonichem, Our process https://sonichem.com/process/, [accessed 09 Jan. 2024].
207 DESNZ, Biomass Strategy, 2023, page 76, https://assets.publishing.service.gov.uk/media/64dc8d3960d123000d32c602/biomass-strategy-2023.pdf, [accessed 09 Jan. 2024].
208 Ricardo AEA, DESNZ UK Biomass Availability Model, [accessed 09 Jan. 2024].
209 Velocys, Plans submitted for the first waste to jet fuel plant in the UK and Europe https://velocys.com/2019/08/20/plans-submitted-for-the-first-waste-to-jet-fuel-plant-in-the-uk-and-europe/, [accessed 10 Jan. 2024].
210 Fiberight, https://fiberight.com/technology/, [accessed 10 Jan. 2024].

considered as a significant source of biomass in 2050. The anticipated availability of residual biogenic waste in 2050 is around 2.6 million tonnes[211].

7.5 Agri-food Residues

Agri-food residues is a broad group of biomass feedstock including milling residues and by-products from food production e.g., dietary and cereal products. The availability of agri-food residues is estimated to be around 1.3 million tonnes.

For example, it is estimated that the Scottish whisky industry produces around 242,000 tonnes of by-products alone, with around 33% of this currently utilised as animal feed.[212]

7.6 Alignment of UK Domestic Feedstock and Target Chemicals

The target chemicals selected by this study could each be produced from a variety of feedstocks. For example, ethanol is currently produced from arable crops (i.e., wheat and sugar beet). However, it could also be produced from lignocellulosic biomass resources, or from various agri-food process residues.

Based on stakeholder engagement it is evident that certain feedstocks are more likely to be used for the production of specific chemicals. An overview of this potential feedstock to chemical relationship is shown in Figure 40.

Certain chemical feedstock relationships can be further defined based on feedstocks targeted by technology developers. For example, Celtic Renewables are building their acetone/butanol/ethanol business model on the use of agri-food process residues (e.g., process co-products from the whiskey industry) and reject potatoes. As another example, Fiberight are investigating the production of lactic acid from residual biogenic waste separated from municipal solid waste using their HYDRACYCLE™ technology. Existing UK ethanol production is based on the use of arable crops which is not considered to change in the medium term but could expand to include lignocellulosic feedstocks in the longer term (i.e., beyond 2035).

The production of the solvent Cyrene™ is based on the chemical conversion of cellulose, and so, it targets lignocellulosic feedstocks such as forest harvest residues and potentially agricultural harvest residues.

211 Ricardo AEA, DESNZ UK Biomass Availability Model, [accessed 09 Jan. 2024].
212 Scottish Government, Distillery by-products, livestock feed and bio-energy use: report, https://www.gov.scot/publications/distillery-products-livestock-feed-bio-energy-use-scotland/pages/5/, [accessed 16 Jan. 2024].

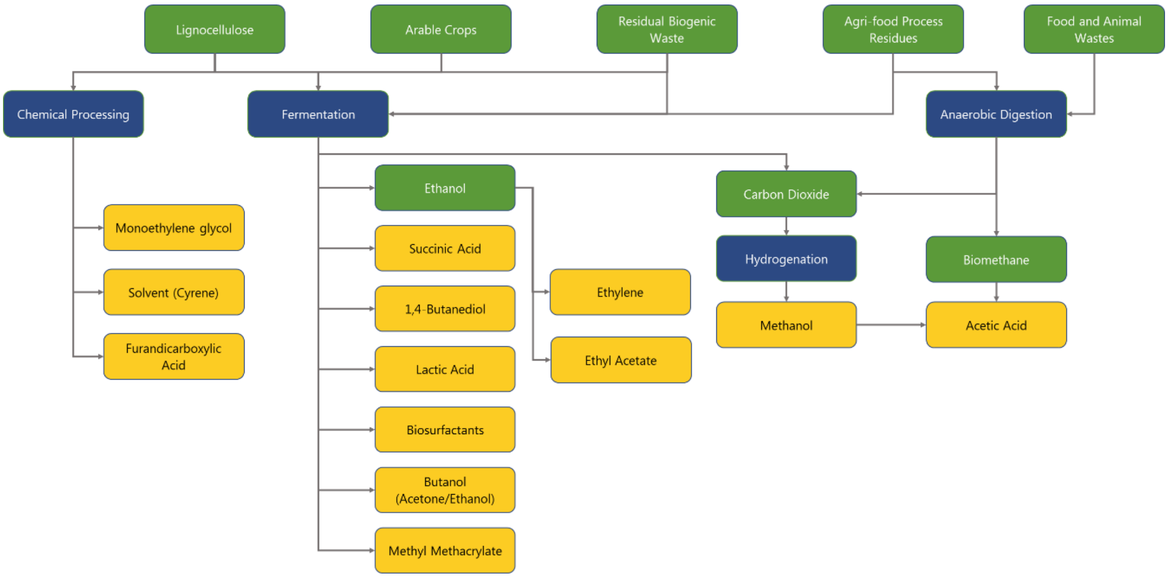

Figure 40. The envisaged relationship between UK feedstock and selected target chemicals.

Bio-based monoethylene glycol can be produced via ethanol. However, new technology development favours direct production from sugar *via* the catalytic hydrogenolysis of glucose. The source of sugar this direct production process uses could be derived from arable crops or from lignocellulosic feedstocks, as is being demonstrated by UPM in Germany.

7.7 Summary of Feedstock Requirements and Availability

There are significant levels of uncertainty associated with estimating biomass resource availability, especially over longer time horizons. The feedstock requirements for the targeted chemicals are summarised in Table 21. The estimates of feedstock availability are derived from modelling underpinning the Biomass Strategy[208], with the exception of arable crops where current gross production is provided for context. The estimates of biomass resource availability described in the Biomass Strategy and used as the basis for this assessment is the total estimated availability across the whole bioeconomy and is not available solely for bio-based chemical production. However it may be considered conservative and therefore, brief commentary is provided to highlight areas of particular uncertainty.

Chemical	Potential	Feedstock requirements	Feedstock availability	Added value co-product production	Commentary
Lactic Acid	Lactic acid, as a polylactic acid plastic precursor is a growing market.	A 50,000 tonnes lactic acid plant would require around 175,000 tonnes of glucose. Any source of fermentable glucose is potentially suitable.	Current UK focus is on the use of residual biogenic waste of which there is a projected 2.5 million tonnes to 2050. Residual biogenic waste is estimated to be 40% glucose (as cellulose)	-	-
Monoethylene glycol	The UK imports over 50,000 tonnes per year.	A 50,000 tonnes monoethylene glycol plant would require around 75,000 tonnes of glucose. Any source of glucose is potentially suitable. Lignocellulosic biomass requirement would be 400,000 tonnes.	Lignocellulosic biomass availability is assessed to be 10 million tonnes in 2050.	Monoethylene glycol production from lignocellulosic biomass also results in the production of monopropylene glycol, lignin based functional materials and industrial sugar (from hemicellulose) as co-products.	The availability of lignocellulosic biomass is sensitive to the development of biomass crops and could be significantly higher than 10 million tonnes in 2050.
Ethyl Acetate	Directing UK bio-based ethanol capacity could produce 550,000 tonnes of ethyl acetate.	UK wheat-based ethanol production requires around 2.2 million tonnes if operating at capacity.	Current UK annual wheat production is in the range of 12-16 million tonnes. Availability is considered to be the current ethanol capacity requirement of 2.2 million tonnes.	Wheat based ethanol products provides a source of valuable animal feed protein and high-quality carbon dioxide suitable for use in food and drink applications.	Arable crop demand for ethanol production is well established. Increases in supply/demand are not considered in this report. However, the scope to increase the supply of sugar beet in the UK has been considered.
Ethylene	Directing UK bio-based ethanol capacity could produce 375,000 tonnes of ethylene.	UK wheat-based ethanol production requires around 2.2 million tonnes if operating at capacity.	Current UK annual wheat production is in the range of 12-16 million tonnes. Availability is considered to be the current ethanol capacity requirement of 2.2 million tonnes.	Wheat based ethanol products provides a source of valuable animal feed protein and high-quality carbon dioxide suitable for use in food and drink applications.	Arable crop demand for ethanol production is well established. Increases in supply/demand are not considered in this report. However, the scope to increase the supply of sugar beet in the UK has been considered.
Methyl methacrylate	Historic UK production capacity was 200,000 tonnes.	Not determined due to process uncertainty. Potentially 500,000 tonnes of glucose, may be required.	Any source of fermentable glucose could be used. Current UK annual wheat production is in the range of 12-16 million tonnes. The UK has the current capacity to process 8 million tonnes of sugar beet and produce up to 1.2 million tonnes of sugar per year.	-	Process routes to methyl methacrylate in development and therefore feedstock type and volume are uncertain.

Methanol	The UK imports around 600,000 tonnes of methanol annually.	840,000 tonnes of carbon dioxide. 120,000 tonnes of hydrogen	Biogenic carbon dioxide is available as a by-product of ethanol production (~500,000 tonnes based on current UK ethanol capacity), anaerobic digestion (750,000 tonnes projected potential), and from biomass to power plants (8 million tonnes projected potential)	-	Bio-based ethanol production produces high quality carbon dioxide suited to health and food/drink applications which may limit supply for industrial uses.
Butanol/Acetone/Ethanol	Typical annual imports of butanol have been between 10 and 20,000 tonnes over the last 10 years. Imports of acetone are over 100,000 tonnes per year.	A 10,000 tonne plant would require a supply of around 25,000 tonnes of fermentable carbohydrate.	Feedstock availability is uncertain as the process can accept multiple feedstock streams including whiskey draff, pot ale and reject potatoes. 1.3 million tonnes of agri-food by-products are estimated to be currently available.	Potential for protein rich co-product as animal feed.	Co-location of production with food and drink businesses allows the use of high moisture content agri-food process streams such as draff and pot ale from whiskey production.
Biosurfactant	Biosurfactants are a growing market	A 10,000 tonne plant would require around 5,400 tonnes of glucose (equivalent to 8,200 tonnes of wheat) and 9,200 of rapeseed oil. The required glucose could be obtained from residual biogenic waste.	Current UK annual wheat production is in the range of 12-16 million tonnes. Residual biogenic waste is projected to be 2.5 million tonnes in 2050. Residual biogenic waste is estimated to be 40% glucose (as cellulose)	-	-
Furandicarboxylic acid	Typical annual imports of terephthalic acid have been above 40,000 tonnes over the last 10 years.	A 10,000 tonne plant would require around 15,000 tonnes of glucose (22,000 tonnes of wheat or alternatively 41,000 tonnes of lignocellulosic biomass)	Current UK annual wheat production is in the range of 12-16 million tonnes.	-	Process routes to furandicarboxylic acid are in development and therefore feedstock type and volume are uncertain.
1,4-Butanediol	A large global market. Bio-based production is at an early stage of commercial adoption.	A 10,000 tonne plant would require around 20,000 tonnes of glucose (30,000 tonnes of wheat).	Current UK annual wheat production is in the range of 12-16 million tonnes. The UK has current capacity to process 8 million tonnes of sugar beet and produce up to 1.2 million tonnes of sugar per year.	-	Feedstock requirements are sensitive to the assumed process yields.
Succinic acid	A platform chemical with significant market potential.	A 10,000 tonne plant would require around 14,000 tonnes of glucose (22,000 tonnes of wheat).	Current UK annual wheat production is in the range of 12-16 million tonnes. The UK has capacity to process 8 million tonnes of sugar beet and produce up to 1.2 million tonnes of sugar per year.	-	Feedstock requirements are sensitive to the assumed process yields.
Dihydrolevoglucosenone	Opportunity to replace solvents with toxicity concerns e.g., DMF and NMP	A 10,000 tonne plant would require around 200,000 tonnes of lignocellulosic feedstock.	Lignocellulosic biomass availability is assessed to be 10 million tonnes in 2050. In 2021, the UK imported 9.1 million tonnes of wood pellets for use in energy production.	Biochar is produced which can be used a fuel or carbon sink, and also in a number of potential chemical applications.	Production could be aligned to UK biomass imports where biomass pellets are processed with the produced biochar used for electricity production (BECCS).
Acetic acid **Biomethane replacing natural gas in the production of acetic acid.**	2.8 TWh of natural gas could be substituted based on current domestic requirement.	2.8 TWh of biomethane.	In 2022, 6.2 TWh of biomethane was injected into the UK gas grid.	Digestate is produced alongside biogas during anaerobic digestion. Digestate is rich in nutrients and nitrogen, commonly used as an organic fertilizer in agriculture. The upgrading of biogas to produce biomethane results in the production of biogenic carbon dioxide.	The potential to increase biomethane supply is considerable with an order of magnitude increase being possible.

Table 21. Summary of target chemicals, feedstock requirements and availability

7.8 One Million Tonne Production Scenario.

In order to examine the potential for bio-based chemical production and the associated environmental and economic impacts[213] the following hypothetical scenario was examined.

> The UK produces one million tonnes of bio-based and bio-attributed chemicals per year.
>
> Production is composed of six biorefineries, each having an output of 100,000 tonnes of bio-based chemicals, and six biofactories each with an output of 50,000 tonnes of bio-based chemicals. An additional 100,000 tonnes of production results from the manufacture of bio-attributed acetic acid.

The feedstock requirement for the six biorefineries (lactic acid, monoethylene glycol, ethyl acetate, ethylene, methyl methacrylate and methanol) is hypothetically distributed across several biomass types based on current infrastructure (e.g., ethanol production) and current commercial activities (e.g., lactic acid and monoethylene glycol). With the exception of cereal straw in the case of methyl methacrylate production, feedstock requirements are not considered as unduly prohibitive.

- Around 950,000 tonnes of wheat grain would be required for ethyl acetate and ethylene, this represents 43% of current ethanol capacity.
- Lactic acid production would require 350,000 tonnes of residual biogenic waste, this represents 13% of availability in 2050.
- Producing monoethylene glycol from forest biomass would require around 425,000 tonnes of feedstock. This represents around 14% of available forest products and residues, or 14% of waste wood.
- Routes to bio-based methyl methacrylate are still developmental and therefore biomass requirements are uncertain. Based on a hypothetical process yield of 40% from glucose, production would require around 935,000 tonnes of cereal straw which is above estimated straw availability; therefore the cultivation of biomass crops would be required to provide feedstock.
- Methanol production would require around 140,000 tonnes of carbon dioxide, this represents 28% of the carbon dioxide that could be captured annually from UK ethanol production. Additionally CO_2 could be sourced from anaerobic digestion plants or captured via BECCUS activities. Planned BECCS units at Drax have the potential to capture 8 million tonnes of CO_2 each year[214].

The feedstock requirements for the six biofactories can also be distributed across biomass types although given the target chemicals there is a focus on the availability of fermentable sugar for the production of butanol/acetone/ethanol, biosurfactants, 1,4-butanediol and succinic acid. The specific nature of the Cyrene™ production process i.e., the co-production of a large volume of biochar as a

213 See associated project report on environmental and economic impacts,
214 DRAX, Drax submits plans to build world's largest carbon capture and storage project, https://www.drax.com/press_release/drax-submits-plans-to-build-worlds-largest-carbon-capture-and-storage-project/, [accessed 05 Feb 2023].

fuel, mean that integration with the UK bioenergy value chain, specifically the import of biomass pellets should be considered.

- The production of butanol/acetone/ethanol is targeted towards co-products from agri-food industries, specifically whisky distillery residues (draff and pot ale) and reject potatoes. The volume of feedstock required is dependent on the fermentable sugar content. Around 125,000 tonnes of fermentable sugar would be required.[215]
- Fermentation processes to produce novel biosurfactant requires an input of fermentable sugar and vegetable oil. The sugar requirement would be around 27,000 tonnes (equivalent to 41,000 tonnes of wheat grain) with an additional 45,000 tonnes of rapeseed oil.[216]
- The production of furandicarboxylic acid would require around 207,000 tonnes of forest residues.[217]
- Fermentation processes to produce 1,4-butanediol could require around 100,000 tonnes of fermentable sugar (equivalent to 149,000 tonnes of wheat) although optimised processes[218] could require significantly less.
- Fermentation processes to produce succinic acid would require around 75,000 tonnes of fermentable sugar (equivalent to 111,000 tonnes of wheat grain).
- Dihydrolevoglucosenone (Cyrene™) is produced alongside a large volume of biochar. One million tonnes of lignocellulosic feedstock would be required to feed a 50,000 tonne dihydrolevoglucosenone plant.[219]

The production of bio-attributed acetic acid involves the attributed use of biomethane injected into the UK gas grid at the acetic acid production site to generate synthesis gas which is then used to carbonylate methanol and produce acetic acid with a bio-attributed biomass content of 47%. Producing 100,000 tonnes of 47% bio-based acetic acid would require around 0.43 TWh of biomethane.[220]

Based on this feedstock assessment the UK has the required feedstock availability to produce one million tonnes of the selected target chemicals.

215 Calculation based on a private communication in confidence, Celtic Renewables, 2023.
216 Calculation based on a private communication in confidence, Holiferm, 2023.
217 Calculation based on a private communication in confidence, Corbion, 2020.
218 Wallace et. al. Engineering biology for sustainable 1,4-butanediol synthesis, Trends in Biotechnology, Volume 41, Issue 3, 2023, Pages 286-288. https://www.sciencedirect.com/science/article/pii/S0167779923000240, [accessed 23 Jan. 2024].
219 Calculation based on a private communication in confidence, Circa, 2024.
220 Calculation based on a private communication in confidence, Ineos, 2023.

Chemical	Production (tonnes)	Feedstock type (volume tonnes)	Percentage of feedstock availability*
Lactic Acid	100,000	Biogenic fraction of MSW (350,000)	13% (based on 2050 Biomass Strategy projections)
Monoethylene glycol	100,000	Forest products, residues and waste wood (425,000)	7% (based on 2050 Biomass Strategy projections)
Ethyl Acetate	100,000	Existing UK ethanol production (380,000)	17% (based on wheat to feed current ethanol capacity)
Ethylene	100,000	Existing UK ethanol production (565,000)	26% (based on wheat to feed current ethanol capacity)
Methyl methacrylate	100,000	1) Agricultural field residues (935,000) 2) Biomass crop (772,000)	1) 108% (based on 2050 Biomass Strategy projections) 2) 39% (based on 2050 Biomass Strategy projections)[221]
Methanol	100,000	Biogenic carbon dioxide (from bioethanol and biomethane production) (140,000)	28% (based on existing bioethanol capacity), 2% of proposed BECCS plans at DRAX.
Butanol/Acetone/Ethanol	50,000	Agri-food process residues (125,000 tonnes of fermentable carbohydrate).	24% (based on 2050 Biomass Strategy projections, assumes 40% fermentable carbohydrate)
Biosurfactant	50,000	Sugar (from wheat grain or sugar beet) (27,000)	2% (based on current UK annual sucrose production)
Furandicarboxylic acid	50,000	Forest products and residues (207,000)	3% (based on 2050 Biomass Strategy projections)
1,4-Butanediol	50,000	Sugar (from wheat grain or sugar beet) (100,000)	8% (based on current UK annual sucrose production)
Succinic acid	50,000	Sugar (from wheat grain or sugar beet) (75,000)	6% (based on current UK annual sucrose production)
Dihydrolevoglucosenone	50,000	Imported biomass pellets (1,000,000)	11% (based on current imports)
Acetic acid (47% bio-based)	100,000	Biomethane (0.43TWh)	7% (based on current grid injection). 2% (based on 2050 grid injection of 30TWh)

Table 22. Summary of feedstock type, volume and availability for a one million tonne chemical supply scenario. *For established arable crops, volumes are taken for current production which is considered a conservative estimate of 2050 availability.

221 Note: Biomass Crop volume projections out to 2050 are uncertain and dependent on Government policy actions, availability could be around 13 million compared to the 2 million tonnes used as the basis of availability.

7.9 Potential Beyond A One Million Tonne Scenario

To assess the potential to produce over one million tonnes of the target chemicals, the potential for available feedstock to support increased production was considered. The potential to expand production of each target chemical was then rated red, amber, green (RAG rated) (Table 23). Actions to allow/enable a greater volume of production based on changing or increasing the availability of feedstock was also considered (Table 23).

Chemical	Potential to increase production	RAG Rating (production ↑ multiple)	Actions to enable/support further increases in production
Lactic Acid	The biogenic fraction of MSW is likely to be in demand for bioenergy uses e.g., aviation fuel.	(0)	A switch in feedstock to biomass crops in conjunction with increasing in yields and cultivation area of biomass crops.
Monoethylene glycol	Feedstock requirements suggest potential for increased production.	(2)	Switch in feedstock to cellulosic sugar from biomass crops. Biomass crop availability stimulated through an increase in yields and cultivation area.
Ethyl Acetate	Current ethanol production could support increasing production. One UK wheat ethanol plant could support around 300,000 tonnes of ethyl acetate production.	(3)	Support for and deployment of cellulosic ethanol production.
Ethylene	Current ethanol production could support increasing production. One UK wheat ethanol plant could support around 200,000 tonnes of ethylene production.	(2)	Support for and deployment of cellulosic ethanol production.
Methyl methacrylate	Feedstock availability is potentially highly restricted based on requirements.	(0)	Increase in yields and cultivation area of biomass crops. Improve process yields to reduce feedstock requirements.
Methanol	The demand for food grade carbon dioxide is likely to restrict feedstock availability.	(0)	Focused development of carbon dioxide capture within the AD industry. Carbon dioxide captured through BECCS deployment used for methanol.
Butanol/Acetone/Ethanol	Production model plays to multiple small scale production plants accessing distributed agri-food process residues.	(0)	Ensure bioenergy policies do not inhibit accessibility to agri-food process residues.
Biosurfactant	Feedstock requirement small in respect to potential supply.	(2)	Increase UK production of fermentable sugar through increase sugar beet cultivation and processing. Switch in feedstock to recovered sugar from MSW or cellulosic sugar from biomass crops. Biomass crop availability stimulated through an increase in yields and cultivation area.

Furandicarboxylic acid	Feedstock requirement small in respect to potential supply.	(2)	Increase UK production of sugar through increased sugar beet cultivation and processing. Switch in feedstock to recovered sugar from MSW or cellulosic sugar from biomass crops. Biomass crop availability stimulated through an increase in yields and cultivation area.
1,4-Butanediol	Increasing production would apply pressure on available sugar feedstock supply but, as process yield improvements are likely, increases are considered possible.	**(2)**	Improve process yields to reduce feedstock requirements. Increase UK production of fermentable sugar through increase sugar beet cultivation and processing. Switch in feedstock to recovered sugar from MSW or cellulosic sugar from biomass crops. Biomass crop availability stimulated through an increase in yields and cultivation area.
Succinic acid	Increasing production would apply pressure on available sugar feedstock supply but increases are considered possible.	**(2)**	Improve process yields to reduce feedstock requirements. Increase UK production of fermentable sugar through increase sugar beet cultivation and processing. Switch in feedstock to recovered sugar from MSW or cellulosic sugar from biomass crops. Biomass crop availability stimulated through an increase in yields and cultivation area.
Dihydrolevoglucosenone	Biomass import volumes demonstrate potential to increase production. Assumed that 4 million tonnes of biomass pellets are diverted from bioenergy use with produced biochar returned to bioenergy value chain	(4)	Production must be integrated with UK bioenergy value chains.
Acetic acid (47% bio-based)	Biomethane grid injection volumes (which are likely to increase) demonstrate potential to increase production.	(6)	Chemical production needs to be considered with biogas and biomethane support policies.

Table 23. The potential to increase chemical production beyond a one million tonne scenario. Value in brackets within the RAG rating denotes the potential to increase production by a multiple of the volume produced in the one million tonne scenario.

On the basis of this assessment there is the potential to increase production of selected chemicals to over 2 million tonnes.

Chemical	RAG Rating (production ↑multiple)	Extended production scenario (tonnes of production)	Indicative fraction of available feedstock without process yield improvements.
Lactic Acid	(0)	100,000	13% (based on 2050 Biomass Strategy projections)
Monoethylene glycol	(2)	200,000	14% (based on 2050 Biomass Strategy projections)
Ethyl Acetate	(3)	300,000	50% of current ethanol capacity
Ethylene	(2)	200,000	50% of current ethanol capacity
Methyl methacrylate	(0)	100,000	39% (based on 2050 Biomass Strategy projections)
Methanol	(0)	100,000	28% (based on 2050 Biomass Strategy projections)
Butanol/Acetone/Ethanol	(0)	50,000	24% (based on 2050 Biomass Strategy projections)
Biosurfactant	(2)	100,000	4% of current sucrose production
Furandicarboxylic acid	(2)	100,000	6% (based on 2050 Biomass Strategy projections)
1,4-Butanediol	(2)	100,000	16% of current sucrose production
Succinic acid	(2)	100,000	12% of current sucrose production
Dihydrolevoglucosenone	(4)	200,000	44% of currently imported biomass
Acetic acid (47% bio-based)	(6)	580,000	40% current grid injection 12% future grid injection
Total		2,230,000	

Table 24. Production potential of selected chemicals

8 Production Scenario

To examine the economic and environmental impact of production of the target bio-based chemicals across the 2030, 2040 and 2050 timeframes a deployment scenario was created. The scenario builds on the following hypothesis.

1) Chemicals with pathways at TRL8 and CRI1 or above, also having a strong UK stakeholder association are deployed by 2030, biorefinery and bio-attributed chemicals are produced at 50,000 tonnes and biofactory chemicals are produced at 10,000 tonnes.
2) By 2040, all target chemicals are produced in the UK, the production of ethyl acetate from ethanol has scaled from 50,000 tonnes to 100,000 tonnes and ethylene is produced at 200,000 tonnes (representing the full capacity of one UK wheat ethanol plant dedicated to ethylene production). Lactic acid production has scaled from 10,000 tonnes to 50,000 tonnes and both methyl methacrylate and methanol are produced at initial volumes of 10,000 tonnes. Biofactory chemicals commercially established by 2030 increase in scale from 10,000 tonnes to 50,000 tonnes. Production of bio-attributed acetic acid grows from 50,000 tonnes to 200,000 tonnes as biomethane availability grows.
3) By 2050, all bio-based chemical production has been scaled. Production of ethyl acetate and ethylene consume one hundred percent of UK ethanol production. Other biorefinery chemicals are produced at 100,000 tonnes with the exception of monoethylene glycol which takes advantage of the volume for forest feedstock to reach 200,000 tonnes of production. Of the original biofactory chemicals, biosurfactant production has been scaled to 100,000 tonnes, however butanol remains at 50,000 tonnes due to feedstock limitations. Dihydrolevoglucosenone has scaled to 200,000 tonnes of production taking advantage of the UKs import of biomass for electricity production with carbon capture (BECCS). Acetic acid production utilises biomethane, fully replacing the use of natural gas as a chemical feedstock.

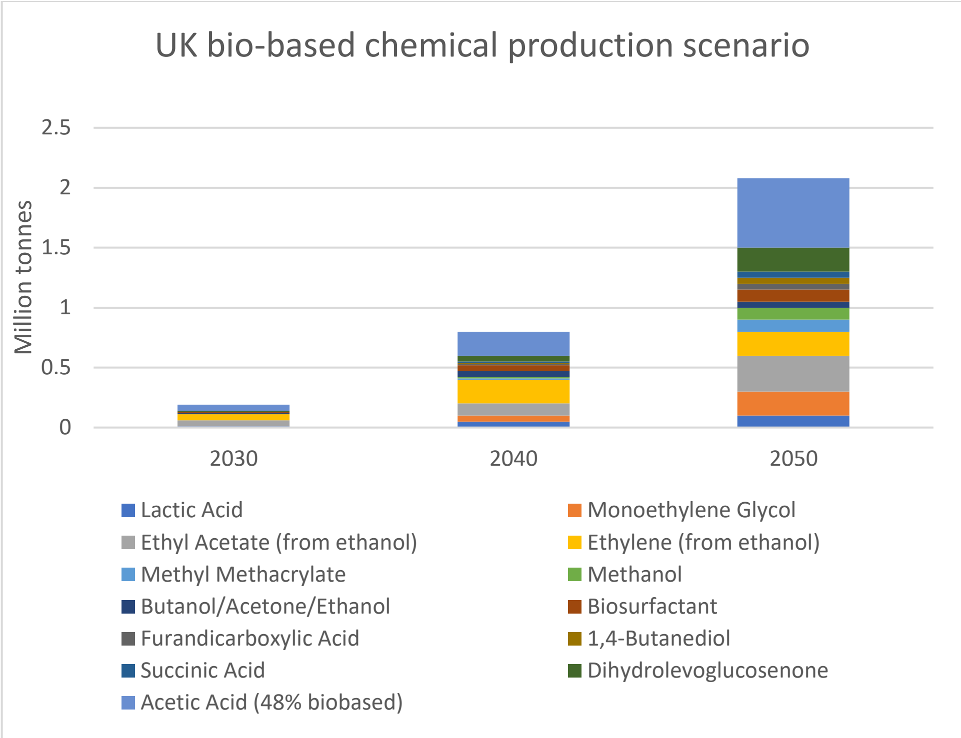

Figure 41. Bio-based chemical production scenario (2030, 2040, 2050)

		Production Million Tonnes		
	TRL/CRI	2030	2040	2050
Lactic Acid	8/1	0.01	0.05	0.1
Monoethylene Glycol	9/2	0	0.05	0.2
Ethyl Acetate (from ethanol)	9/2	0.05	0.1	0.3
Ethylene (from ethanol)	9/3	0.05	0.2	0.2
Methyl Methacrylate	4-5/1	0	0.01	0.1
Methanol	9/1	0	0.01	0.1
Butanol/Acetone/Ethanol	9/2	0.01	0.05	0.05
Biosurfactant	9/2	0.01	0.05	0.1
Furandicarboxylic Acid	7-8/1	0	0.01	0.05
1,4-Butanediol	9/3	0	0.01	0.05
Succinic Acid	9/2	0	0.01	0.05
Dihydrolevoglucosenone	8/1	0.01	0.05	0.2
Acetic Acid (48% biobased)	9/1	0.05	0.2	0.58
Total		0.19	0.80	2.08

Table 25. Bio-based chemical production scenario (2030, 2040, 2050)

9 Summary

Through a process of literature review, extensive stakeholder engagement and expert assessment, thirteen bio-based target chemicals were selected as representative chemicals around which the environmental and economic impacts of production in the UK could be assessed.

Initially a long list of 69 potential bio-based chemicals and materials, it was reduced through stakeholder engagement and literature review to 15 production pathways/target chemicals.

The selection process centred on three questions,

1. Is the potential for production in the UK credible and achievable? A qualitative assessment reviewed whether the UK produced the necessary feedstock, and both the technology and commercial readiness of production pathways to chemical targets.
2. Would production be meaningful in respect to possible greenhouse gas emissions reductions? In order to achieve meaningful reduction it was assumed that production/demand should be above 10,000 tonnes per year and therefore, the potential scale of production was reviewed.
3. Is production in the UK plausible and realistic? Stakeholder engagement and expert knowledge was used to identify UK interest in the production or use of the chemical (ideally a UK chemical company producing/using or looking to produce/use).

The selected chemicals can be placed into three groups.

- The first group (biorefineries) are chemicals aligned with biorefinery scale production, typified by existing large-scale production of bio-based products (e.g., lactic acid) and large scale production of bio-based intermediates (e.g., ethanol), or products with large markets and stakeholders interested in large scale production. It is reasonable to expect biorefinery capacities to be >100,000 at commercial maturity.
- The second group consists of bio-based chemicals at an earlier stage of commercial maturity, with initial commercial production likely to be at scales of around 10,000 tonnes. These biofactory processes may ultimately scale to biorefinery size but may also take advantage of feedstock availability or be scaled according to market demand.
- The final group is the bio-attributed group, this includes bio-based feedstocks capable of being processed in existing petrochemical chemical complexes.

A second review of the 15 production pathways/target chemicals resulted in the removal of two pathways, giving a final selection of 13 target chemicals.

The pathways removed in the second round of review related to the use of co-products generated during the production of renewable diesel and sustainable aviation fuel (SAF). This typically involves the production of hydrogenated vegetable oil (HVO)/ hydroprocessed esters and fatty acids (HEFA) but could also include alcohol to jet (AtJ) and Fischer-Tropsch derived products. Fischer-Tropsch processes produce varying amounts of propane and naphtha which can served as feedstocks for petrochemical steam crackers. However, there is significant uncertainty around the volume of propane that could become available based on UK production, and due to the conversion of the UK's naphtha-based steam crackers to gas (ethane) feedstocks, the UK no longer has the capability to process naphtha. Based on this understanding it was decided that these pathways did not meet the selection criteria defined above.

Of the twelve target bio-based chemicals (excluding bio-attributed acetic acid) selected, three are commercial processes, five are near commercial with demonstrated technology, three are pre-commercial with processes being demonstrated, and one is in technical development. Although not commercially practiced, bio-attributed acetic acid could be readily commercialised if commercial requirements around the price of biomethane could be achieved.

A RAG rating of the reviewed pathways (Table 2) shows qualitative assessment of pathways against the criteria at the outset of the review.

A deeper dive into the potential for UK production was undertaken by aligning the target chemicals with potential feedstocks. This relationship was explored within a scenario of one million tonnes of bio-based chemical production. The scenario was based on six notional biorefineries producing 100,000 tonnes of lactic acid, ethyl acetate, ethylene, methyl methacrylate and methanol, six production facilities (biofactories) producing butanol/acetone/ethanol, a biosurfactant, furandicarboxylic acid, 1,4-butanediol, succinic acid and the solvent dihydrolevoglucosenone (Cyrene™).

Feedstock alignment was based on stakeholder information and expert judgement. The feedstock alignment demonstrates the flexibility in feedstock choice for chemical production. Feedstocks considered ranged from established feedstocks currently in large scale use (e.g., wheat grain for ethanol production, through to MSW and biomass crops as a source of cellulosic sugar, the use of animal slurries and food waste to produce biomethane, and the use of carbon dioxide to produce methanol).

In reviewing chemical production and feedstock volumes it is necessary to consider the production of important co-products. The process of wheat grain to ethanol produces valuable animal feed. Pyrolysis type processes, such as the production of Cyrene™ creates large volumes of biochar fuel. Therefore, the integration and interplay of bio-based chemical production with agriculture and energy markets warrants further research.

Ethanol and methanol are both chemical and fuel products, this creates the opportunity of technology development to serve two markets, but also creates a direct competition between markets for product and feedstock. There is therefore a need to ensure alignment in policy support for particular molecules, whether used as fuel or as chemical intermediates/products.

An assessment of feedstock availability suggests that domestic UK biomass could support the production of over 2 million tonnes of bio-based chemicals by 2050. Beyond 2050, there is further potential to expand production based on the utilisation of biogenic carbon dioxide to produce methanol.

However, the production potential is highly dependent on several factors which are uncertain. Key factors include bioenergy market development, both as an enabler of biomass supply (e.g., imported biomass) and as a competitor of feedstock (e.g., biomethane); the development and supply of biomass crops along with the economics of cellulosic sugar production; the commercial attractiveness of chemicals produced from food and feed crops; and the future availability of low carbon hydrogen to support methanol production.

10 Appendices

10.1 Technology Readiness Level Definitions

Adapted from Buchner et al. 'Specifying technology readiness levels for the chemical industry'.[222]

TRL	Stage	Description	Tangible output
1	Idea	Opportunities identified; basic research translated into possible applications	Idea / rough concept / vision / strategy paper
2	Concept	Technology concept and/or application formulated, patent research conducted	Technology concept formulated, list of solutions, future R&D activities planned
3	Proof of concept	Applied laboratory research started, functional principal reaction proven	Proof of concept (in laboratory)
4	Preliminary process development	Concept validated in laboratory environment, scaleup preparation started, shortcut process models found	Documentation of reproduced and predictable (quantitative) experiment results, multiple alternative process concepts evaluated
5	Detailed process development	Process models found, property data analysed, simulation of process and pilot plant using bench scale information	Parameter and property data, few alternative process concepts evaluated in detail
6	Pilot trials	Pilot plant constructed and operated with low-rate production; products approved in final application	Working pilot plant
7	Demonstration and Full-scale engineering	Demo plant constructed and operating with equipment comparable to full scale production. Pilot plant optimized (optional)	Pilot plant optimized
8	Commissioning	Full-scale plant constructed	Finalized and qualified system and building plant
9	Production	Full-scale plant, production operated over the full range of conditions at industrial scale and environment	Full-scale plant tested and working

222 Industrial and Engineering Chemistry Research, 10.1021/acs.iecr.8b05693, American Chemical Society (ACS) available at https://doi.org/10.14279/depositonce-11483 [accessed 05 Feb 2023].

10.2 Commercial Readiness Index

Adapted from the Australia Renewable Energy Agency (ARENA) 'Commercial Readiness Index for Renewable Energy Sectors'.[223]

CRI	Stage	Description
6	"Bankable" grade asset class	Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.
5	Market competition driving widespread deployment	Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.
4	Multiple commercial applications	Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources.
3	Commercial scale up	Commercial proposition being driven by technology proponents and market segment participants – publicly discoverable data driving emerging interest from finance and regulatory sectors.
2	Commercial trial	Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
1	Hypothetical commercial proposition	Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.

223 Commercial Readiness Index https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf., [accessed 05 Feb 2023].

NNFCC is a leading international consultancy with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products.

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ANNEX 4

Economic Analysis

February 2024

Economic potential of bio-based chemicals & materials

Department for Energy Security & Net Zero

This report should be read in conjunction with associated reports as part of project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

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Previous Version: Draft v0.5, 29th November 2023
Distribution of this version: Draft Final, 15th January 2024

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Introduction

In early 2023 the Department for Energy Security & Net Zero (DESNZ)[224] commissioned a consortium led by NNFCC to conduct research into the environmental and economic potential of bio-based chemicals and plastics in the UK. The research is expected to highlight areas in which biomass use in the chemicals and plastics sectors can best contribute to growing innovation and the economy, while also helping meet the UK's Net Zero ambitions.

Overall Study Approach & Method

The research methodology consisted of five main strands (1) Project Initiation; (2) Literature Review; (3) Original Research; (4) Quantitative Analysis; and (5) Synthesis and Reporting. An overview of the methodology is presented in Figure 1.1 below and described briefly in subsequent paragraphs for ease of reference.

Figure 1.1 – Methodology Overview

A **literature review**, including grey literature was conducted with a focus on existing and nascent technologies for producing bio-based chemicals and materials. The extensive review covered numerous aspects of bio-based chemicals and plastics research and innovation, including but not limited to relevant environmental and economic information.

Industry and academic stakeholders were engaged in **original research** via one-to-one interviews and online surveys to elicit expert opinion on the UK's current status, opportunities and challenges, and future scenarios for bio-based chemicals production in the UK. A stakeholder mapping exercise will produce stakeholder groups that are 1) core, 2) secondary and 3) peripheral to the study. A series of briefing sessions and promotion via social media was used to raise awareness of the study. One-to-one interviews with strategically important stakeholders spanning industry, policy and academia gathered in-depth information regarding a) the current status of bio-based chemical production in the UK; b) opportunities and challenges and c) future scenarios for bio-based chemical production in the UK. Stakeholders consulted included large, medium and small businesses, government officials, academics and trade bodies. In total the study engaged with 69 individual

224 At that time the Department for Business Energy and Industrial Strategy (BEIS)

organisations. Fifty organisations completed the survey and 50 organisations were interviewed.

Quantitative analysis involved both economic and environmental data collection and analysis. The economic analysis examined current and potential future growth of bio-based chemicals and plastics market incumbents at firm-level, and sought to apply detailed economic data and assumptions to generate broader estimates using experimental methods. Further detail regarding the approach and methodology used to produce the findings contained in this report is provided in Section 1.2 below.

A final **evidence synthesis and reporting** stage (of which this working paper is part) synthesised quantitative and qualitative evidence to provide clear and systematic responses to each of the research questions.

Economic Analysis Approach & Methodology

The economic analysis sought to take a two-pronged approach. Firstly, the study sought to conduct a 'macro' economic analysis by collating company-level data for UK bio-based chemicals and materials companies using a combination of Standard Industrial Classification (SIC) codes[225], existing company lists[226] and experimental key terms-based identification of companies across several proprietary and open-source platforms including Bureau van Dijk and Beauhurst. Identification and refinement of the company dataset involved a 5-stage process, described in Appendix 1.

Secondly, the study also sought to take a 'micro' or 'bottom-up' approach to produce estimates of the economic potential of specific 'target chemicals' identified as offering economic potential to the UK based on expert opinion and stakeholder contributions. It was originally envisaged that data pertaining to costs and revenues associated with bio-based chemicals and materials products could be collected directly from a number of the strategic companies involved in the stakeholder engagement component of the study. A detailed economic data collection template (Appendix 1) was designed and circulated to company representatives that gave consent to be re-contacted following the initial stakeholder interview. A number of follow-up consultations were held and, while several companies were willing to contribute further economic data to the study, ultimately only three companies provided data at the level of granularity required to inform the bottom-up analysis.

Subsequently, in a further effort to capture data that could inform the bottom-up analysis the study team sought to gather relevant data from more than two dozen relevant research papers and credible sources of chemicals data[227]. While almost 100 unique datapoints were gathered against in-scope target chemical pathways, ultimately the coverage and consistency of the data did not allow for robust analysis of cost and benefits associated with individual target bio-based chemicals.

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225 SIC codes 201, 202 and 721.
226 Including NNFCC's internal company lists.
227 Including but not limited to https://www.chemanalyst.com/.

Therefore, following DESNZ recognition of the challenges associated with the “bottom-up” analysis, and in consultation with NNFCC, it was agreed that chemicals and plastics trade data would be used to provide some higher-level assessment of the economic potential of individual target chemicals (Section 3).

Methodological Limitations

It is important to note that the methods used to estimate bio-based chemicals and materials economic activity in this study are experimental. They do not use traditional Standard Industrial Classification (SIC) codes and are therefore not consistent with formal economic statistics produced by the Office for National Statistics, the Chemicals Industry Association, or other central government departments. Specifically, the analyses presented in this report use novel approaches to estimate the proportion of bio-based activity within shortlisted chemicals and materials companies using web-based employment data.

Macroeconomic Analysis

This section of the working paper presents key findings from i) company-level analysis and ii) the analysis of imports data described in Section 1.

Chemical Sector Headlines

In 2023 the Chemicals Industry Association (CIA) estimates that there are 4,415 chemicals businesses in the UK, employing 151,000 people, generating c.£203k in Gross Value Added (GVA) per employee. On this basis, the UK chemical sector contributes almost £31bn in GVA to the UK economy. This annual value added represents almost one sixth of all manufacturing related GVA in the UK[228] and is almost double the level of value added via the manufacture of pharmaceuticals in the UK[229]. The CIA also estimates that the UK chemicals sector exports approximately £54bn of manufactured goods annually and was responsible for 17.5% of total UK business R&D expenditure in 2023[230].

Company-Level Analysis

Given the significant contribution of the current chemicals and materials sector to the UK economy, it is clear that converting even a fraction of that activity to become bio-based could offer considerable economic opportunity. This sub-section therefore uses company data, gathered and classified using experimental methods to understand where, more specifically, this economic potential could be realised in the short-to-medium term (i.e., to 2040).

'Serviceable Addressable' Bio-based Opportunity

Following identification and refinement of a list of more than 2,500 companies potentially within the scope of the study, the macroeconomic (company-level) analysis focusses on a shortlist of 568 'in-scope' companies (see Appendix 1). These 568 companies are referred to as the 'Serviceable Addressable Market' for increasing bio-based economic activity because descriptive company information suggests that they already undertake at least some bio-based activity. The purpose of defining the Serviceable Addressable Market for bio-based activity is because it may represent a productive target / baseline for government policies intended to stimulate further growth of bio-based activity in future.

Based on reported company data, in the latest available year for which data is available[231] the companies identified as being within the serviceable UK market for bio-based chemicals and materials generated £60bn in turnover and employed more than 130,000 people globally. Table 2.1 below provides further global economic headlines regarding the Serviceable Addressable Market for UK bio-based chemicals and materials activity.

228 https://www.cia.org.uk/Policy/Economics
229 Comparators taken from ONS Regional Gross Value Added by Industry and Region, 2021 figures.
230 CIA defines the chemicals sector in broad terms as SIC section 201, including manufacture of rubber and plastics in primary forms.
231 Either 2021 or 2022 financial years

Table 2.1 – Serviceable Addressable Market Economic Headlines

Metric (Global, Latest Available Year)	Figure
Turnover	£60bn
GVA	£15bn
Research & Development Expenditure	£680m
Total Grants & Fundraising	£350m
Employees	130k

Source: Bureau van Dijk

UK Economic Activity

A majority of the companies included within the Serviceable Addressable Market are trading predominantly or entirely within the UK. Where this is the case, any economic data captured can be reasonably recorded as being UK-based. However, a small number of larger UK registered companies have global activity that is recorded within UK reported company data. For these companies it is necessary to gather further information to establish the scale of UK operations specifically.

A combination of publicly available annual reports, web-based people data and / or company data obtained from the proprietary data platform Bureau van Dijk was used to estimate the number of employees involved in UK operations. Such adjustments were required for 39 of the 568 in-scope companies (7%). Estimates of UK revenues were subsequently estimated by multiplying UK employment data by global turnover per employee averages.

Table 2.2 – Estimated UK Economic Activity

Metric (UK, Latest Available Year)	Totals (% of Global Total)
Turnover	£20bn (33%)
GVA	£4.4bn (30%)
Employees	37,000 (28%)

Source: Bureau van Dijk, Perspective Economics

Bio-based Economic Activity

As per the approach taken to estimate UK activity as a proportion of global financial reporting data (described above), the study team used a combination of machine-learning enabled company classification, web-based people data and expert industry opinion to estimate the proportion of bio-based UK activity among the 568 in-scope companies.

Defining 'Dedicated' & 'Diversified' UK Chemicals & Materials Companies

As a first step in estimating the proportion of economic activity attributable to bio-based activity within the Serviceable Addressable Market the study team used descriptive company information drawn from annual reports and web data to train and apply a deep learning or Large Language Model (LLM).

Based on descriptive information for the full set of 568 companies the LLM was prompted to estimate whether each company had a 'High', 'Medium' or 'Low' level of bio-based activity. The study team reviewed all of the LLM generated results, of which ~75% were found to be reasonable. Manual adjustments were made to the remaining ~25% of companies based on a combination of industry expertise from NNFCC and desk-based review.

Based on manual review of the LLM results, any company deemed to have a 'High' level of bio-based activity was included within a 'Dedicated' group. Any company deemed to have either 'Medium' or 'Low' levels of bio-based activity were included in a separate 'Diversified' group. Table 2.3 below provide an illustration of the type of companies included within the Dedicated and Diversified groupings.

Table 2.3 – Dedicated & Diversified Company Illustrations

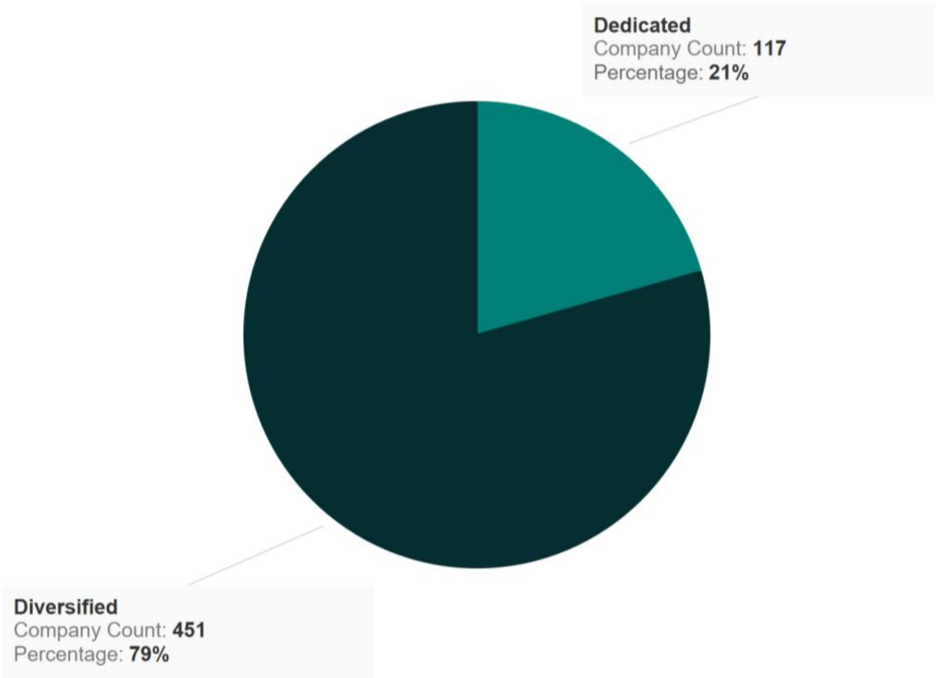
Grouping	Company Name	Company Description
Dedicated	Croda	Croda is a global specialty chemical manufacturer that creates, produces and sells high-performance ingredients and technologies for a wide variety of industries, using smart science to enhance lives. Scaling our biotechnology capabilities is one of our core strategic priorities and a key aspect of how we will enhance the sustainability of our processes, contributing to the achievement of our sustainability target to increase our use of bio-based raw materials to over 75% by 2030.
	Futamura	Futamura is engaged in the production and distribution of polypropylene films, polyester films, cellophane products, non-woven fabrics, fibrous casing products, activated carbon, and phenolic resin laminate for packaging, industrial, environment, and medical and health applications. The company is the world's leading producer of sustainable cellulose packaging films.

	Argent Energy	Argent Energy processes a variety of raw materials, such as food waste and oil, into biodiesel, which it supplies to oil and fuel companies. We specialize in the supply of high grade, sustainable diesel for fleet operators, delivering to over 100 UK depots from Kent to Dundee. All the bio--component of our diesel is made in the UK from waste fats and oils. This ensures it is the most sustainable available and we deliberately exclude any raw materials that could also be used for food or feed. Argent has two manufacturing facilities for waste--based biodiesel and following a recent £75million investment, the production capacity will be 145 million litres per year.
Diversified	Johnson Matthey	Global chemicals and sustainable technologies company that enables a cleaner and healthier world. The company is engaged in the development and manufacture of specialty chemicals that focuses on catalysis, precious metals, fine chemicals, process technology, and emission controls. It is a global leader in science that enables cleaner air, improved health and more efficient use of natural resources. The emission control technologies segment produces catalysts, which control harmful emissions from cars and other light duty vehicles powered by various types of fuel. The process technologies segment produces catalysts, additives, and absorbents; and delivers services to the petrochemical, biochemical, syngas, oil refining, and gas processing industries.
	INEOS Industries	INEOS operates a multinational chemicals manufacturing company, including the production of petrochemicals and specialty chemicals. INEOS' businesses have introduced bio-based feedstocks into a range of bio-attributed polymers and chemicals. At all INEOS sites offering such products, each step in the supply chain has been fully certified by ISCC or RSB. In both cases the final product carries an attribution according to the displacement of fossil fuel-derived raw materials.
	Synthomer	Synthomer develops and produces high-performance chemical products for multiple markets worldwide, including adhesives, coatings, construction, health & protection, performance materials, energy solutions, and paper, carpet & foam. Our innovation team is finding new ways to adapt our existing products and design new ones with even greater benefits. For example our Suncryl® HP 114 water-based polymer contains more than 56% bio-based raw materials, replacing chemicals made from fossil fuels.

Source: Bureau van Dijk, Beauhurst, Web Data

Of the 568 companies included within the Serviceable Addressable Market, 21% are categorised as being ‘Dedicated’ bio-based companies (n=117) and 79% are categorised as being ‘Diversified’ bio-based companies (n=451).

Figure 2.1 – Dedicated & Diversified Company Segmentation



Source: Perspective Economics

Economic Contribution of ‘Dedicated’ Bio-based Companies

The analysis provides a range for the economic contribution of ‘Dedicated’ biobased companies based on two scenarios.

Scenario 1: In all but one instance, 100% of UK economic activity for companies identified as being ‘Dedicated’ biochemicals and materials companies was included in the aggregated totals. Based on consultation with the largest Dedicated company – Croda – and given the significance of Croda’s economic contribution, a lower proportion of 85% of UK economic activity was included within the aggregated total bio-based economic headlines.

Scenario 2: Applying a more conservative estimate assuming that on average 85% of economic activity among all ‘Dedicated’ companies is biobased (rather than 100% of activity applied to companies other than Croda in Scenario 1).

Table 2.4 – Dedicated Bio-based Company UK Activity (Scenario 1)

Metric (UK, Latest Available Year)	Scenario 1	Scenario 2
Count of Companies	117	117
Turnover	£1.1bn	£1bn
Employment	2,300	2,000
GVA	£340m	£290m
Grants & Fundraising	£200m	

Source: Bureau van Dijk, Perspective Economics (N.B. figures are rounded)

On this basis, Dedicated bio-based chemicals and materials companies employ between 2,000 and 2,300 people in the UK, generate between £1bn - £1.1bn in turnover annually, contribute between £290m - £340m in Gross Value Added to the UK economy each year. These companies have secured almost £200m in external grants and fundraising[232].

Economic Contribution of 'Diversified' Bio-based Companies

To estimate the proportion of bio-based activity within 'Diversified' bio-based companies, the study team used a combination of web-based people data and feedback from a workshop with industry experts held in York in late 2023. By comparing the number of people employed in 'bio' based roles in the UK, against overall UK employment figures, the study team was able to generate an estimated percentage of bio-based activity for 'Diversified' companies of different sizes. Prior to the workshop with industry experts, analysis of web-based people suggested the following:

- 1% bio-based employment in large Diversified companies.
- 4% bio-based employment in medium-sized Diversified companies.
- 1% bio-based employment in small and micro-sized Diversified companies.

Following the external industry validation workshop, these proportions were adjusted upwards to reflect the insight of industry experts, as follows:

- 2% bio-based employment in large 'Diversified' companies (n=33, 7%).
- 5% bio-based employment in medium-sized 'Diversified' companies (n=77, 17%).
- 1% bio-based employment in small and micro-sized 'Diversified' companies (n=341, 76%).

232 Note that the Total Grants and Fundraising figure includes grants and fundraisings secured at any stage in the company's history since data began being collected by Beauhurst in 2006.

Ultimately, therefore, these proportions have therefore been derived using the upper bound of the percentage range for bio-based employment for each size of company based on web-based people data, together with external research including Renewable Carbon Initiatives, and external stakeholder opinions.

Table 2.5 – Diversified Company Bio-based Activity

Metric (UK, Latest Available Year)	Proportion	Figure
Count of Companies	UK Total	451
Turnover	UK Total	£19bn
	Bio-based	£0.5bn
Employment	UK Total	34,400
	Bio-based	900
R&D Spend	UK Total	£660m
	Bio-based	£14m
GVA	UK Total	£4bn
	Bio-based	£100m

Source: Bureau van Dijk, Perspective Economics

Prominent Bio-based Employers

Table 2.6 below presents the top 10 Dedicated and Diversified bio-based chemicals and materials companies in the UK by measure of bio-based employment.

Table 2.6 – Top 10 Dedicated & Diversified Companies (Employment)

	Dedicated	Diversified
1	CRODA	JOHNSON MATTHEY
2	FUTAMURA (UK Operations)	INEOS
3	ARGENT ENERGY[233]	SYNTHOMER
4	ENSUS	SYNGENTA
5	BIOCATALYSTS	ELEMENTIS
6	BIOLOGICAL PREPARATIONS	BPI
7	GREENERGY BIOFUELS	TENNANTS CONSOLIDATED
8	CORYTON ADVANCED FUELS	VICTREX
9	CELTIC RENEWABLES	WESTLAND HORTICULTURE
10	INGENZA	SCOTT BADER

233 Biofuel companies have been included because of their high potential to transition to bio-based chemical companies.

Source: Bureau van Dijk[234]

Between 2019 and 2021/22, large and medium-sized dedicated biochemicals and materials companies grew revenues by 15% and employment by 13%. Albeit from a lower base, growth among dedicated bio-based chemicals and materials companies between 2019 and 2021/22 was at least as strong as growth among similarly-sized diversified companies (i.e., those driven by non-bio-based activity). Large and medium-sized diversified companies increased revenues by 9% and employment by 1% over the same period[235]. Dedicated biochemicals companies driving economic growth include Biological Preparations Limited, Greenergy Biofuels and Ensus.

Ineos, Synthomer, Johnson Matthey, Perspex International and Pangaia are among the fastest growing Diversified companies, adding between 150 and >5,000 employees to their workforces (including through acquisition) since 2019.

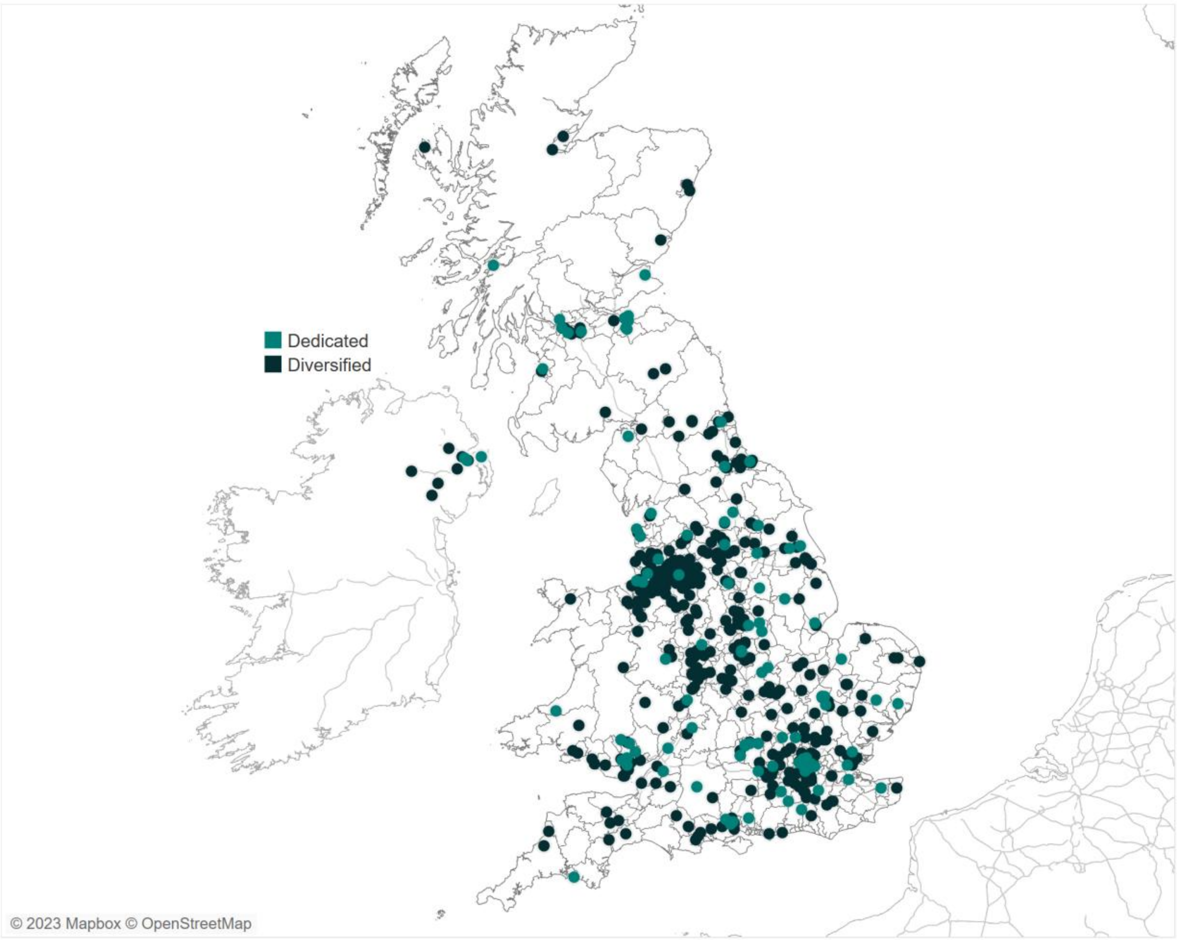
Case Study: Growth in Biocatalysis	JM Johnson Matthey Inspiring science, enhancing life
Johnson Matthey (JM) offers various catalyst technologies to diverse sectors of the economy. In recent years the company has increased its focus on biocatalysts for the pharmaceutical market. Having acquired German enzyme provider X-Zyme in 2010, the company has since invested in computational modelling to reduce the time taken to transform natural enzymes for industrial use. By applying computational-based enzyme engineering techniques, the company expects to expand its biocatalyst product base across pharmaceuticals, agrochemicals, flavours and fragrances. Eventually, JM also expects to reliably and quickly design de-novo enzymes that can catalyse entirely novel chemistry unseen in nature.	

Bio-based Activity Clusters

Analysis of the location of Dedicated and Diversified bio-based chemicals and materials companies typically shows close proximity between the two. There is notable clustering of Diversified companies in the North West with some Dedicated company activity, and pockets of Dedicated company activity within the Golden Triangle, the South East, the Midlands, South Wales, Yorkshire and in Scotland.

234 Top 10 list of Dedicated and Diversified companies excludes companies registered under SIC 20150 – Manufacture of fertilisers and nitrogen compounds based on relevance to policy-making.
235 Note caution due to difference in sample sizes. Dedicated company revenue growth (sample = 16), dedicated company employment growth (sample = 69); diversified company revenue growth (sample = 105), diversified company employment growth (sample = 107).

Figure 2.2 – Registered Office Addresses (Dedicated / Diversified)

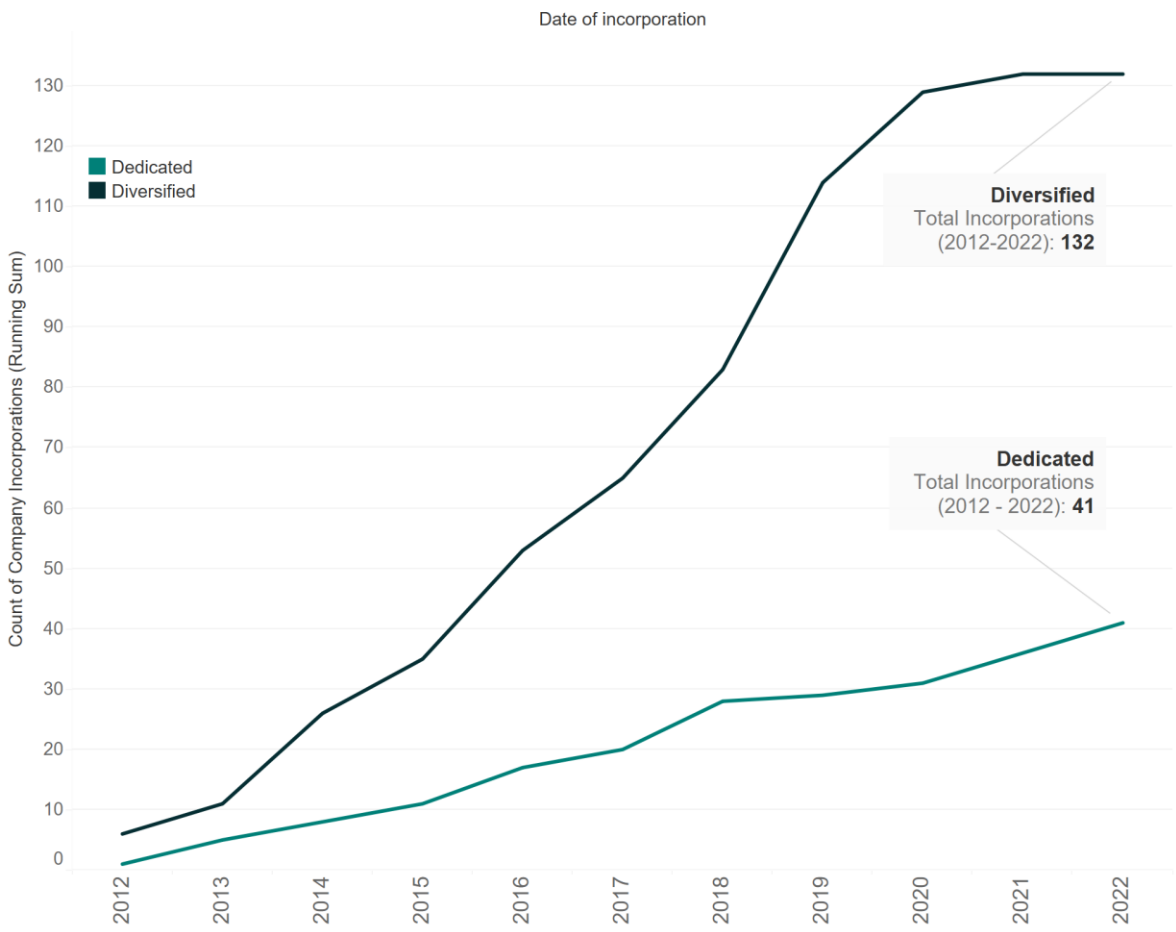


Source: Bureau van Dijk, ONS

Start-Up & Investment Landscape

There has been an upward trend in the number of Dedicated bio-based chemicals and materials company incorporations over the past decade. Approximately one quarter of all new company incorporations (within our dataset) over the past decade have been Dedicated bio-based chemicals and materials companies (Figure 2.3). However, since 2018 the number of new Dedicated company incorporations has not kept pace with Diversified company incorporations, suggesting a need for renewed impetus within the start-up ecosystem if potential future economic opportunities are to be realised.

Figure 2.3 – Company Incorporations (Dedicated / Diversified)



Source: Bureau van Dijk

Dedicated companies have secured more grants and external funding than Diversified companies. A total of 44 Dedicated companies have secured a total of ~£200m in external grants and fundraising. Over the same period, 30 Diversified companies have secured just under £105m in external grants and fundraising. Grant funding accounts for approximately one fifth of total grants and fundraising secured by both Dedicated and Diversified bio-based companies (19% and 20% respectively).

While 'Dedicated' companies make up just one fifth of the Serviceable Addressable Market, they account for more than two thirds of total grants and fundraising secured over the period. While the total value of grants and external fundraising is small in comparison to other sectors, the analysis does suggest some recent appetite to support innovative UK bio-based chemicals and materials companies.

Table 2.7 shows the top 10 Dedicated companies by measure of total grants and fundraising.

Table 2.7 – Top 10 Dedicated Companies (Investment)

	Dedicated Bio-based Company Name
1	CELTIC RENEWABLES LIMITED
2	ALGAECYTES LIMITED
3	NOTPLA LIMITED
4	XAMPLA LTD
5	HOLIFERM LIMITED
6	EPOCH BIODESIGN LTD
7	CELLUCOMP LIMITED
8	INGENZA LIMITED
9	OCEANIUM LTD
10	BIO-SEP LIMITED

Source: Beauhurst

Case Study: Notpla

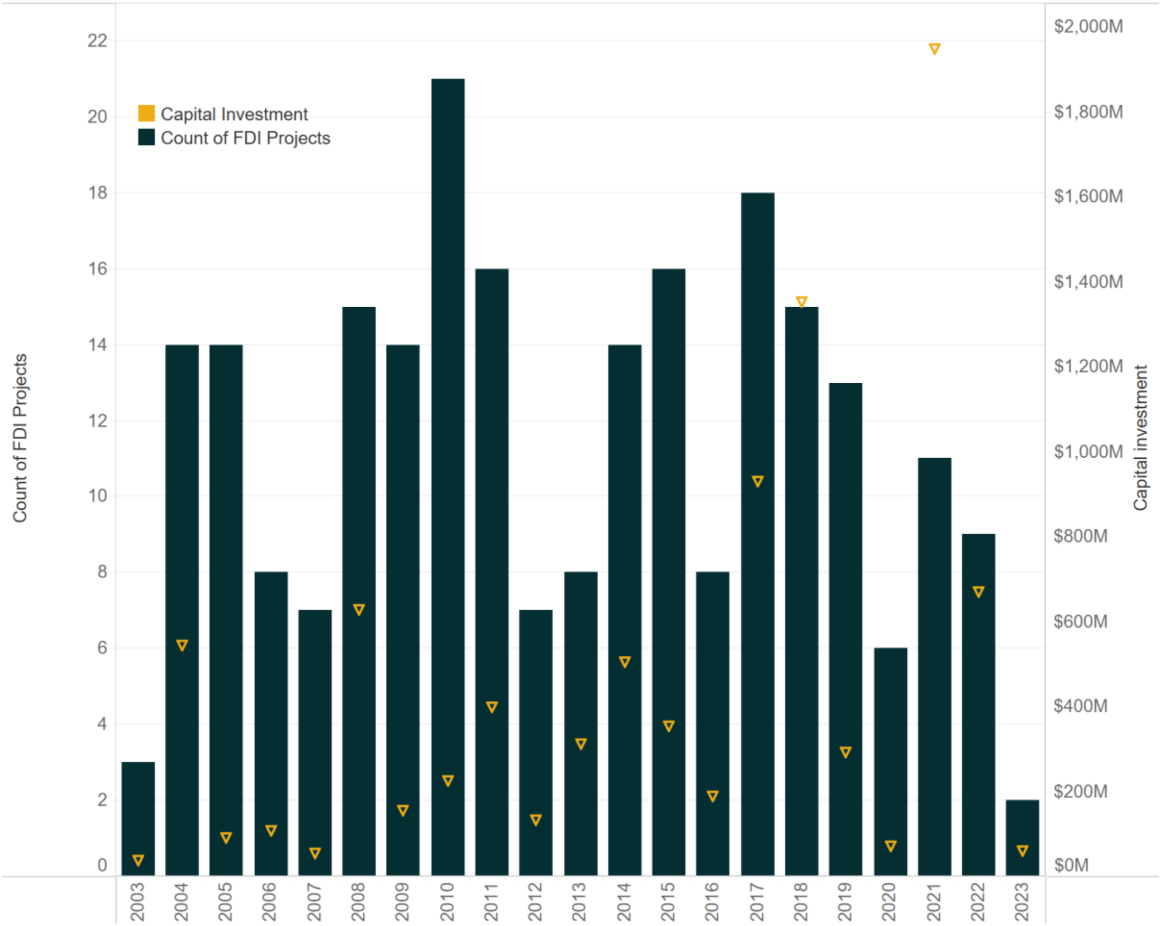
NOTPLA

Incorporated in 2014, London-based Notpla makes home-compostable packaging inspired by nature. Notpla is a non-chemically modified, polysaccharide-based material used to produce packaging products (primarily water bottles) that are among relatively few classified as a natural, organic substance by EU law. Made from seaweed and plants, Notpla packaging biodegrades naturally within weeks. In 2022 Notpla secured an Earthshot Prize in recognition of the company's potential to scale and help deliver against the five Earthshot goals – protecting nature, cleaner air, reviving oceans, building a waste-free world and fixing the climate.

Inward Investment

Analysis of chemicals-related foreign direct investment (FDI) projects into the UK suggest that major international businesses see opportunity in UK chemical manufacturing activity. Since 2003, internationally owned chemicals companies have invested $9bn into UK projects, including but not limited to investments into Grangemouth, Teeside, Runcorn and Fawley. Figure 2.5 shows the number and value of chemicals-related inward investment projects into the UK over time, including substantive investments by international companies such as Sabic, Exxonmobil, Huntsman, Essar Oil and AkzoNobel.

Figure 2.5 – UK Chemicals FDI Projects



Source: FDI Markets

Economic Opportunity – Macroeconomic Company-Level Conclusions

The chemical industry is a major contributor to the UK economy, generating around £31bn in gross value added (GVA) and exporting £54bn in goods annually.

The companies identified by the study as being within the Serviceable Addressable Market for bio-based chemicals and materials generate around £60bn in turnover and employ more than 130k people globally. In 2021/22 these companies invested almost 700m in research and development activity and have secured more than £350m in external grants and fundraising over the past decade. Between 2018 and 2022 Dedicated bio-based chemicals and materials companies have grown revenues and employment.

There is notable clustering of Diversified companies in the North West with some Dedicated company activity, and pockets of Dedicated company activity within the Golden Triangle, the South East, the Midlands, South Wales, Yorkshire and in Scotland.

One hundred and seventeen companies are 'Dedicated' bio-based companies, generating an estimated £1.1bn in UK turnover. Four hundred and fifty-one are 'Diversified' bio-based companies, generating an estimated additional £480m in UK bio-based turnover.

According to the latest available company data, together Dedicated and Diversified companies generate an estimated £1.6bn in UK turnover, contribute £440m in GVA, and employ an estimated c.3,200 people in bio-based roles.

New Dedicated company incorporations have levelled off since 2018, suggesting a need to stimulate the startup ecosystem to realize future opportunities.

Dedicated companies have seen more growth in grants/fundraising than Diversified companies in recent years, accounting for approximately 75% of most recent grant funding and 60% of most recent fundraising within the Serviceable Addressable Market for bio-based activity.

Major international chemical companies see opportunities within the UK and have invested billions of dollars into UK projects over the past 20 years.

Microeconomic Analysis

Following attempts to gather credible economic cost and benefit data for target chemical pathways identified within the stakeholder engagement component of the study, and in consultation with DESNZ, it was agreed that chemicals and plastics trade data would be used to provide some assessment of the economic potential of individual target chemicals.

This section therefore uses data on the UK's trade in chemical and plastics products, both at an aggregate level, and with respect to a subset of chemicals that could feasibly be produced in the UK under the scenarios defined via the stakeholder engagement component of the study. The scenarios, target chemicals and materials are summarised in Table 3.1 below.

Table 3.1 – UK Bio-based Chemical & Material Opportunities

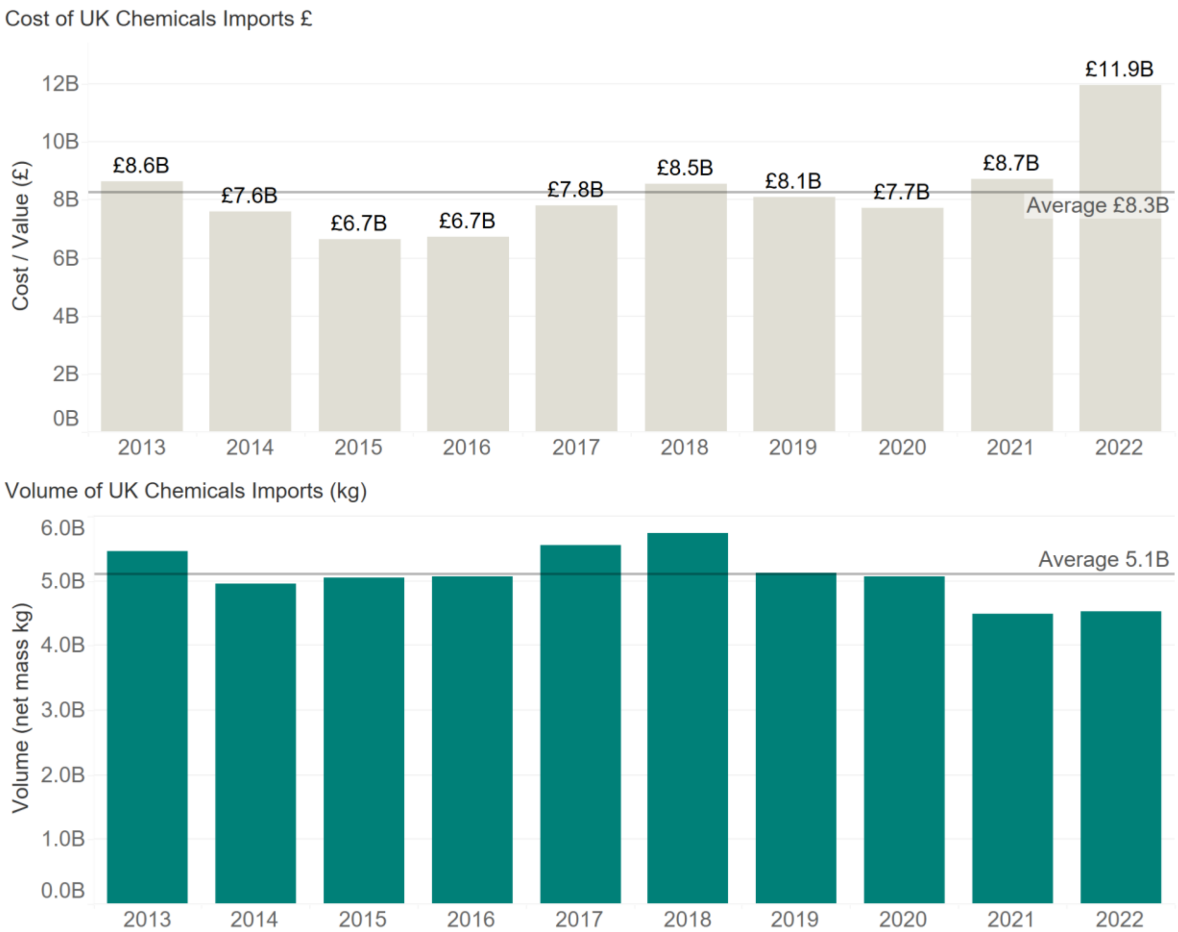
Scenario	Target Bio-based Chemical / Material (Purpose)
Biorefinery	Lactic acid via fermentation (polymer production)
	Monoethylene glycol via sugar hydrolysis (polymer & surfactants)
	Ethyl acetate via ethanol (solvents)
	Ethylene via ethanol (polymer production)
	Methyl methacrylate via fermentation (polymer production)
	Methanol from green hydrogen (methanol)
	Acetic Acid (48% bio-based)
Distributed Biomanufacturing	Butanol, acetone and ethanol through ABE fermentation (solvents)
	Biosurfactants via fermentation (solvents)
	Furandicarboxylic acid (FDCA) and Hydroxymethylfurfural (HMF) through sugar chemistry (surfactants & polymer production)
	Butanediol through fermentation (polymer production)
	Succinic acid via fermentation (polymer production)
	Dihydroevoglucosenone through sugar chemistry (solvents)
Business As Usual	Bio-based propane from SAF production (cracker feedstock)
	Bio-based naphtha from SAF production (cracker feedstock)
	Bio-based methane (feedstock for acetic acid, acetic anhydride and ethyl acetate production)

Source: NNFCC

Organic Chemicals Imports

HMRC's UK Trade Info[236] data shows that in 2022 UK chemicals companies spent almost £12bn on chemical imports. On average, since 2013 UK companies have spent £8.3bn on chemicals imports, yet the volume of chemicals being imported has largely remained constant (Figure 3.2)[237]. Consultation with industry experts suggests that the significant jump in chemical import costs in 2022 is as a result of geopolitical instability.

Figure 3.2 – Total UK Organic Chemicals Imports (2013 – 2022)



Source: HMRC UK Trade Info

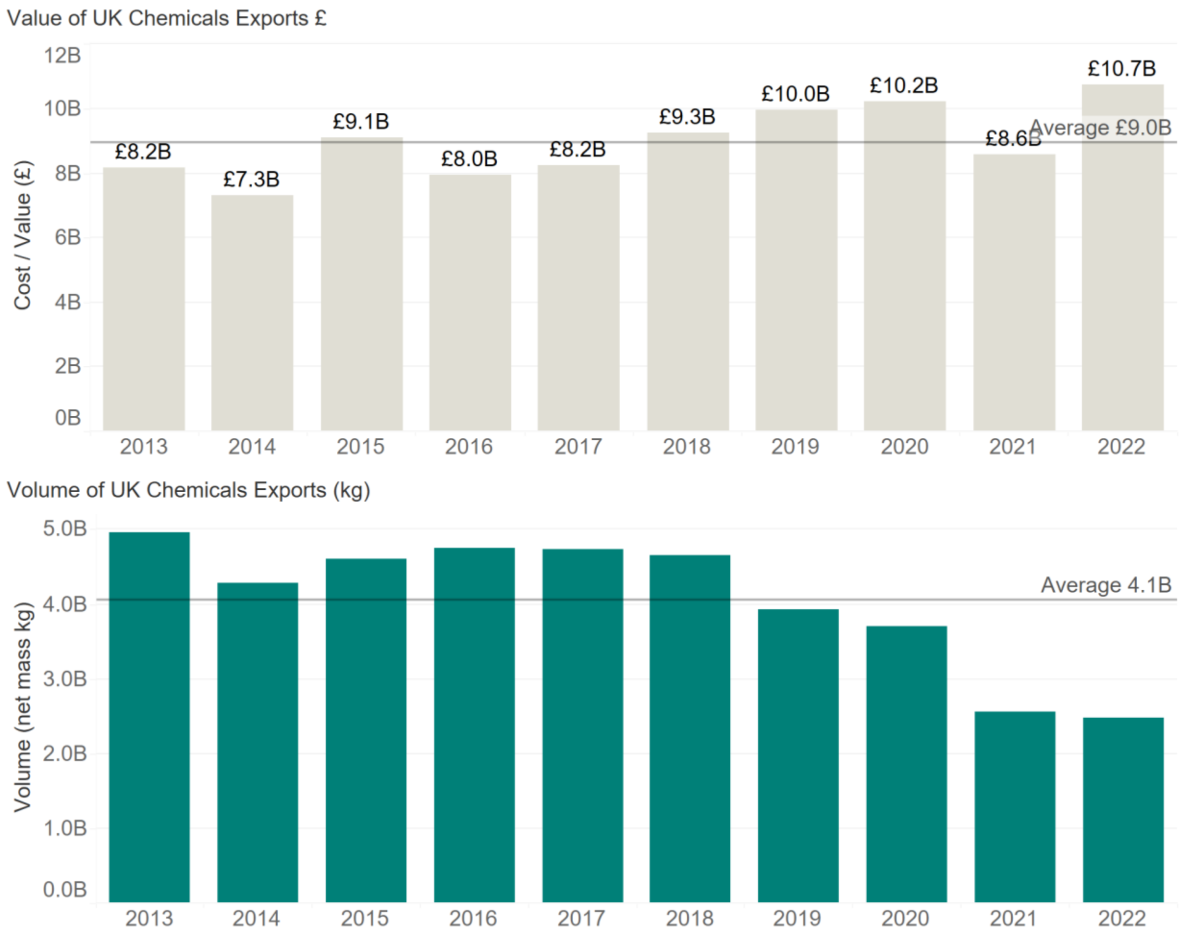
Organic Chemicals Exports

Since 2013 the UK has exported an average of £9bn in organic chemicals. The trend in UK chemicals exports has been upward over the period, from £8.2bn in 2013 to £10.7bn in 2022 (+30%). While the value of UK chemicals exports has been increasing, the quantity of organic chemicals exports fell sharply in 2021/22. This suggests that in 2021 and 2022 the UK stopped exporting significant volumes of low value chemicals. This is likely due to a combination of the impact of COVID on manufacturing operations, and the closure of Sabic's

236 https://www.uktradeinfo.com/
237 Analysis combines EU and non-EU imports and includes non-response estimates.

cracker (Olefins 6) which is one of just three crackers in the UK and the second largest in Europe[238].

Figure 3.4 – Total UK Organic Chemical Exports (2013 – 2022)



Source: HMRC UK Trade Info

238 This cracker had the capacity to produce over 1.3million tonnes of chemicals (ethylene production capacity of 865,000 tonnes/year plus 415,000 tonnes/year of propylene).

Plastics Imports

Similarly, UK Trade data shows that in 2022 UK plastics companies spent £18.5bn on plastics imports. On average, since 2013 UK companies have spent £14.2bn on plastics imports. The volume of plastics imported into the UK over the same time period has remained relatively constant at about 7m tonnes (Figure 3.7).

Figure 3.7 – Total UK Plastics Imports (2013 – 2022)

Source: HMRC UK Trade Info

Plastics Exports

Since 2013 UK companies have exported an average of £9bn in plastics commodities, and exported £3bn more in 2022 than in 2013. The value plastics commodities exported by UK companies has been increasing since 2013, and the value per kilogram of plastics exported has risen particularly sharply since 2020 when the value of plastics exports continued to rise despite falling export quantities.

Figure 3.9 – Value of UK Plastics Exports (2013 – 2022)

Source: HMRC UK Trade Info

Trade in target chemicals and materials

As discussed in the introduction to this Section, the study was unable to obtain granular data that would enable like-for-like analysis of the costs and benefits associated with target biochemical and materials production compared to fossil-based alternatives. In the absence of this data the study analysed import and export data as a proxy for understanding the potential significance of biochemical alternatives to a selection of target fossil-based equivalents. The target fossil-based chemicals and materials are:

1. Acetic acid – used as a building block for the production of paints, coatings and textiles, and across the food, pharmaceuticals and agriculture sectors for preservatives, intermediates and pesticides.
2. Ethylene – used to produce a variety of chemicals and plastics, including polyethylene, and in the manufacture of packaging materials and household products.
3. Lactic acid – used as a preservative, flavour enhancer and acidity regulator in the food and beverage industry, in medical products as IV solutions and dialysis fluids and as a skincare ingredient in the cosmetics industry.
4. Ethyl acetate – used as a solvent in the production of coatings, paints and varnishes for industrial finishes and automotive paints, in the formulation of adhesives and sealants and as a flavour and fragrance agent.
5. Methyl methacrylate – used to produce polymethyl methacrylate (PMMA, or acrylic) for the automotive, aerospace and construction industries, and with applications in medical devices and electronics.
6. Methanol – used as a solvent and additive across the automotive, manufacturing, construction and pharmaceutical sectors, and widely tested as a sustainable fuel.
7. Butanol – input to acrylates and methacrylates to make plastics and resins, and also used as a solvent in the manufacture of paints, coatings, inks and adhesives.
8. Acetone – used as a solvent in manufacturing plastics, fibres and other chemicals, as a paint / coating remover, a cleaning agent in laboratories and industrial settings, a degreasing agent in manufacturing and in the production of adhesives and sealants.
9. Biosurfactants – used in household and industrial cleaning products, cosmetics and personal care products, pharmaceuticals, pesticides and herbicides in agriculture, and emulsifiers for food, ink and coatings.
10. Terephthalic acid (Furandicarboxylic acid (FDCA)) – used in the production of polyethylene terephthalate (PET) for packaging and textiles and as a raw material for making resins and plasticisers.
11. 1,4-Butanediol – used as an intermediate in the production of spandex fibres and thermoplastic engineering polymers with applications in electronics, automotive components and mechanical components.
12. Succinic acid – used in the production of various chemicals, including resins, polyesters and plasticisers and in the synthesis of biodegradable polymers.
13. Dihydrolevoglucosenone – bio-based solvent with potential use as a building block to produce high value chemicals.

Table 3.2 shows the fossil-based chemical codes selected as proxies for estimating the significance of each scenario chemical to the UK economy.

Table 3.2 – Proxy Chemical Commodity Codes

	Scenario Chemical	Proxy Chemical Code(s)
1	Acetic acid	29152900 Salts of acetic acid (excl. inorganic or organic compounds of mercury) 29153100 Ethyl acetate
2	Ethylene	29012100 Ethylene
3	Lactic acid	29181100 Lactic acid, its salts and esters (excl. inorganic or organic compounds of mercury)
4	Ethyl acetate	29153100 Ethyl acetate
5	Methyl methacrylate	29161300 Methacrylic acid and its salts
6	Methanol	29051100 Methanol "methyl alcohol"
7	Butanol	29051300 Butan-1-ol "n-butyl alcohol"
8	Acetone	29141100 Acetone
9	Biosurfactants	34021300 Non-ionic organic surface-active agents, whether or not put up for retail sale (excl. soap)
10	Furandicarboxylic acid (FDCA)	29173600 Terephthalic acid and its salts
11	1,4-Butanediol	29053928 Butane-1,4-diol 29053926 Butane-1,4-diol or tetramethylene glycol
12	Succinic acid	29171920 Ethane-1,2-dicarboxylic acid or butanedioic acid "succinic acid" having a bio-based carbon content of 100% by mass
13	Dihydrolevoglucosenone	Not available

Source: NNFCC

Eight of the target chemicals (highlighted) have been traded in significant volumes over time (c.10,000 tonnes or more). Three of these ‘significant’ chemicals are predominantly exported (Acetic acid, Ethylene, and Ethyl Acetate) and the remainder have been predominantly imported.

Table 3.3 - Balance of Trade in Target Chemicals (10-year average, Tonnes)

	Target Chemical	Trade Balance	Balance of Trade
1	Acetic acid	-130,727	Export
2	Ethylene	-709,213	Export
3	Lactic acid	2,582	Import
4	Ethyl acetate	-128,326	Export
5	Methyl methacrylate	6,866	Import
6	Methanol	783,393	Import
7	Butanol	15,727	Import
8	Acetone	123,502	Import
9	Biosurfactants	60,600	Import
10	Furandicarboxylic acid (FDCA)	44,070	Import
11	1,4-Butanediol	753	Import
12	Succinic acid	-20	Export
13	Dihydrolevoglucosenone	-	-

Source: HMRC UK Trade Info

Table 14 shows the average volumes and values (exports) or cost (imports) for these higher-volume chemicals over the past decade, and the actual value / cost of UK exports and imports over the period (right-most column).

Table 3.4 - Target Chemical Costs, Volumes and Value (10-year average / total, Tonnes)

Scenario Chemical	Trade Balance	Avg. Cost / Value Per Tonne	Volume (Tonnes, 10-Yr Ave)	Average Annual Cost / Value	10-Yr Value
Acetic acid	Export	£1,636	143,808	£106,844,472	£1,068,444,716
Ethylene	Export	£789	738,024	£549,782,422	£5,497,824,218
Ethyl acetate	Export	£685	138,007	£91,731,220	£917,312,195
Total Export Value					£7,483,581,129
Methanol	Import	£265	789,795	£205,651,715	£2,056,517,150
Butanol	Import	£846	15,963	£13,094,050	£130,940,500
Acetone	Import	£585	125,918	£72,422,904	£724,229,040
Biosurfactants	Import	£2,440	82,499	£199,902,573	£1,999,025,735
Furandicarboxylic acid (FDCA)	Import	£1,020	44,085	£40,656,057	£406,560,576
Total Import Cost					£5,317,273,001

Source: UK Trade Info

Trade data shows that over the past decade, UK companies have generated almost £7.5bn in revenue from the sale of fossil alternatives to target chemicals (acetic acid, ethylene and ethyl acetate) and have spent almost £5.5bn on imports of target chemical equivalents (methanol, butanol, acetone, biosurfactants and FDCA). It shows that the UK a) has the capacity and capability to generate substantive revenues from bio-based acetic acid, ethylene and ethyl acetate in future and b) has average annual demand of more than 50k tonnes of fossil equivalents to bio-based methanol, acetone and biosurfactants.

Extending this type of analysis to the target chemical production volumes provides an indication of the potential trade benefit of UK production239. As set out in Table 15 below, based on 2019 import costs and export prices, some of the highest value potential future UK opportunities are in the production of bio-based acetic acid (£270m), ethyl acetate (£191m) and methyl methacrylate (£186m)[240]. With the exception of acetic acid, all figures are assumed to be in addition to the value of fossil-based alternatives.

Table 3.5 - Target Chemical Trade Value Opportunity (Gross)

	Trade Direction	2030 Scenario Production Volume (tonnes)	2040 Scenario Production Volume (tonnes)	2050 Scenario Production Volume (tonnes)	2030 Total Trade Benefit (£)	2040 Total Trade Benefit (£)	2050 Total Trade Benefit (£)
Lactic acid	Import	10,000	50,000	100000	£15,389,009	£76,945,043	£153,890,085
Monoethylene glycol	Import	-	50,000	200000	£ -	£26,745,403	£106,981,611
Ethyl acetate	Export	50,000	100,000	300000	£31,880,053	£63,760,106	£191,280,319
Ethylene	Export	50,000	200,000	200000	£38,310,744	£153,242,977	£153,242,977
Methyl methacrylate	Import	-	10,000	100000	£ -	£18,667,838	£186,678,380
Methanol	Import	-	10,000	100000	£ -	£2,425,093	£24,250,931
ABE	Import	10,000	50,000	50000	£6,717,928	£33,589,641	£33,589,641
Biosurfactant	Import	-	10,000	50000	£-	£25,303,527	£126,517,636
Furandicarboxylic acid	Import	-	10,000	50000	£-	£6,881,527	£34,407,636
1,4-Butanediol	Import	10,000	10,000	50000	£16,478,200	£16,478,200	£82,391,000
Succinic acid	Export	-	10,000	50000	£-	£14,065,000	£70,325,000
Dihydro-levoglucosenone	Export	10,000	50,000	200000	£7,160,000	£35,800,000	£143,200,000
Acetic acid (48% bio-based)	Export	50,000	200,000	580000	£23,319,426	£93,277,702	£270,505,336

Source: UK Trade Info, NNFCC, Perspective Economics

[239] Figures are taken from UK Trade Info and therefore reflect trade prices rather than specific chemical prices which tend to be lower.
[240] Trade direction is based on the balance of UK trade over the past 10 years. Where the UK has been a net importer of scenario chemical equivalents, future trade values reflect import cost savings, plus estimated export values (where not all UK production is required in the UK). Where the UK has been a net exporter of scenario chemical equivalents, future trade values reflect estimated production multiplied by current export prices per tonne (2019, unadjusted). N.B. figures have not been aggregated because the same fossil equivalent chemical is included in more than one scenario. Figures do not reflect any price differential for bio-based alternatives, including for example the likely higher value of FDCA compared to terephthalic acid. Changes to revenue derived from existing production e.g., ethanol and acetic acid are not considered in the report. Production estimates can only be realised if commercial appetite exists to produce bio-based alternatives.

Economic Opportunity – Microeconomic Conclusions

From a trade balance perspective, UK companies have generated more in target chemicals exports than they have spent on imports over the past decade, driven by export of cracker products (ethylene and propylene).

Removing cracker products from the target chemicals group flips the average balance of trade over time by more than £0.5bn, from positive c.£300m to negative c.£300m, highlighting the historic significance of cracker products to the UK economy.

Looking specifically at scenario chemicals, estimates produced using scenario production values and trade data suggests that future potential opportunities may be highest in the production of bio-based acetic acid, ethyl acetate, and methyl methacrylate.

Conclusions

Given appropriate support and subject to feedstock availability, the chemical sector has the scale, capacity and transferrable skills necessary to make the UK a leading location for the production of bio-based chemicals and materials on the basis that:

- The UK chemical sector contributes almost £31bn in GVA to the UK economy and accounts for almost one fifth of total UK business R&D expenditure in 2023.
- Global multinational chemicals companies including Sabic, ExxonMobil, Huntsman, Essar Oil and AkzoNobel see considerable opportunity in UK chemicals and materials operations.
- Companies within the serviceable addressable market for bio-based chemicals and materials employ around 130,000 people, generate £60bn in turnover and have invested £680m in R&D.

The UK already as a core of bio-based chemicals and materials activity on which to build. One hundred and nineteen dedicated biochemicals and materials companies identified through this study already generate more than £1bn in turnover and increased their employment base by almost 20% between 2018 and 2022.

Growing bio-based chemicals and plastics activity in the UK will require further deep and meaningful engagement with strategically significant companies across the serviceable addressable market. Engagement should focus on:

- Expanding existing bio-based activity among larger dedicated biochemicals companies such as Croda, Futamura, Argent Energy and Ensus.
- Supporting high-growth companies such as Celtic Renewables and Holiferm to continue improving processes, reducing costs and accessing new markets.
- Engaging with larger diversified biochemicals and materials companies such as Johnson Matthey, Syngenta and Ineos to convert more of their UK activity to bio-based.
- Reigniting the start-up bio-based chemicals and plastics ecosystem, ideally with 'buy-in' from existing bio-based market incumbents and / or larger diversified companies.

From a trade balance perspective, UK companies have generated more in target chemicals exports than they have spent on imports over the past decade, driven by export of cracker products (ethylene and propylene).

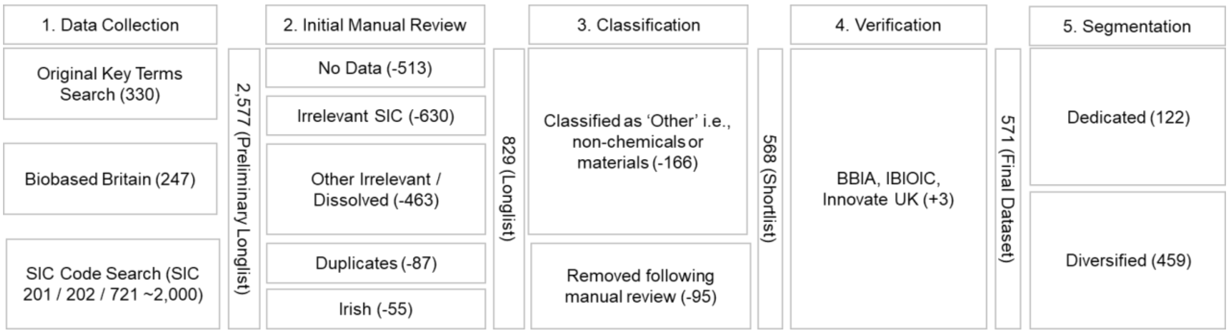
Removing cracker products from the target chemicals group flips the average balance of trade over time by more than £0.5bn, from positive c.£300m to negative c.£300m, highlighting the historic significance of cracker products to the UK economy.

Looking specifically at scenario chemicals, estimates produced using scenario production values and trade data suggests that future potential opportunities may be highest in the production of bio-based acetic acid, ethyl acetate, and methyl methacrylate.

Appendix 1 – Macroeconomic Data Analysis Approach

Identification and refinement of the company dataset involved a 5-stage process, illustrated in Figure I.1 and described in further detail below.

Figure I.1 – Data Identification & Refinement



Source: Perspective Economics

Stage 1: Initially, more than 2,500 companies were identified as being potentially within the scope of the study based on key term searches within proprietary datasets including Bureau van Dijk.

Stage 2: A 'Preliminary Longlist' was subjected to structured manual review. During this initial review companies were removed if:

1. No reported company revenue or employment data existed;
2. Companies were categorised using irrelevant SIC codes[241];
3. Companies were recorded as being inactive / dissolved;
4. More than one registered company ID was included (duplicate entries); or
5. Companies were registered in Ireland.

Stage 3: The subsequent 'Longlist' of 829 companies was classified using a combination of machine learning[242] and manual review[243]. At this stage, companies were removed if they:

1. Were classified as 'Other' i.e., not being involved in chemicals or materials activity;
2. Were classified as chemicals or materials companies but were reasoned (by applying LLM technology to descriptive information) not to have any bio-based activity; or
3. Did not appear to have any bio-based activity following further manual review.

241 Such as, for example, plastic moulding, dyes & pigments, industrial gases, mining, oil refining.
242 An industry-leading large language model (LLM) was trained using descriptive information regarding example in-scope bio-based chemicals and plastics companies to classify the long-list of companies into three categories namely i) 'biochemicals', ii) 'bioplastics' or iii) 'other'.
243 Members of the study team reviewed the results of the LLM classification and undertook further manual refinement to remove companies that did not appear to have any bio-based activity.

Stage 4: A ‘Shortlist’ of 568 companies was then subjected to further review against existing trade body membership lists and other sources of company data known to be relevant to the scope of the economic analysis[244]. Three additional companies were added to the Shortlist.

Stage 5: Descriptive information (including trade descriptions extracted from company accounts and web-based descriptive information) for a final set of 570 in-scope companies was used to determine – again using machine-learning – the extent of bio-based activity in each company (see Section 2.2.2).

244 Trade body membership lists (https://bbia.org.uk/bbia/membership/, https://www.ibioic.com/about) and recent recipients of Innovate UK awards identified additional, largely small or micro businesses which were added to the Master dataset for analysis.

ANNEX 5

Environmental Analysis

Imperial College London

Bio-based Chemicals Environmental Assessment

This report should be read in conjunction with associated reports as part of project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223)

Prepared by

Onesmus Mwabonje
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Introduction

The quality of life we currently enjoy is greatly attributed to chemicals and materials produced from non-renewable resources with fossil-based feedstocks. To ensure that quality of life is sustainably maintained in the future, it is essential that we transition to a circular economy, where measures are put in place to reuse or recycle materials at their end-of-life (Ewing et al., 2022). A paradigm shift in the chemical industry with a focus on chemicals and materials production from renewable carbon feedstocks such as biomass is urgently needed. Efficient conversion methods for biomass-derived feedstocks to chemicals are required to achieve this transition. Climate change concerns, depletion of fossil oil reserves, and the rising prices of chemicals has also led to an increasing interest in the possibility of converting bio-based feedstocks into valuable chemical compounds (Mortimer et al., 2009). For chemical companies to remain competitive, it is essential that they find every possible way to transition to bio-based chemicals to reduce their greenhouse gas (GHG) emissions (Brennan et al., 2023).

Investing in bio-based feedstock sources and conversion technologies can help close the gap to net zero within the chemical industries. Biomass feedstocks are typically complex, heterogeneous materials, containing a diverse range of molecules such as carbohydrates, proteins, oils, and lignin (Brew, 2006). These feedstocks are chemically rich and, as they come from green plants, potentially have low climate change impact as plants do not add carbon dioxide directly to the atmosphere (Ewing et al., 2022). However, fossil energy sources are currently used in the cultivation of crops and the processing of feedstock into the final product. To determine whether there are any advantages in producing chemicals from biomass, an environmental assessment using life cycle assessment (LCA) approaches needs to be carried out (Mortimer et al., 2009). The most used feedstocks to produce bio-based chemicals by fermentation are carbohydrates. Sugars such as glucose and sucrose can be obtained from sucrose or starch containing plants. The common sources of sucrose include sugarcane and sugar beet, while common sources of starch are, wheat, corn, cassava and sorghum among others. Out of these crops, wheat, sugar beet and to some extent corn are commonly cultivated in the United Kingdom. The use of these feedstocks to produce bioethanol has generated some discussion, as they are also suitable for consumption by humans and animals, raising concerns around competition for land use with food and feed production (Tomei and Helliwell, 2016). Therefore, the use of sugars from non-edible lignocellulosic biomass residues, such as corn stover, wheat straw, non-food crops such as Miscanthus or forestry residues, known collectively as second-generation biomass feedstocks has been gathering interest recently (Sigoillot and Faulds, 2016). Evidently, the use of biotechnology to provide alternative routes to produce chemicals has had several successful outcomes. The challenge is to develop efficient methods by which to obtain monomeric sugars from these feedstocks and methods for the utilisation of pentose sugars present in hemicellulose, in addition to the glucose from cellulose (Ewing et al., 2022). Currently, fermentation processes based on second generation feedstocks are mainly in the developmental phase, while most commercial processes to produce bio-based chemicals rely on the use of first-generation sugar feedstocks.

Aims and Objectives

The overarching aim of this study was to provide an insight into which bio-based chemicals offer the largest potential for GHG emission savings relative to the fossil chemicals counterparts that perform the same function. In terms of scope, this study has looked at pathways which convert biomass feedstocks into bio-based chemicals by means of biochemical or thermochemical conversion through a literature review. These bio-based products are then compared to functionally equivalent petrochemical products. This study also looked at identifying the strengths and limitations of applying LCA approach for quantifying the environmental impact for bio-based chemicals. The bio-based chemicals considered were identified during a stakeholder engagement held in June 2023. The literature review also was used to Identify constraints of LCA methodology for assessing biochemical production pathways.

Environmental Assessment Approach

Quantitative analyses on the environmental impacts related to bio-based chemicals and materials produced are relatively scarce and fragmented. Usually, environmental results are published in the form of academic and industry research case studies. The literature search we conducted was restricted to a given functional unit i.e., per kg of chemical or material. In addition, we developed a data requirement sheet that was circulated to key stakeholders for primary data collating for a bottom up LCA study. Unfortunately, it was not possible to obtain the primary data from stakeholder companies, either data was unavailable or considered too commercially sensitive to share. However, some companies were willing to share their LCA and sustainability reports which we used to supplement GHG emission data obtained from literature.

We also reviewed and updated some emissions factors and the global warming potentials (GWP) for chemical LCA spreadsheet models that were developed by North Energy Associates Ltd for the National Non-Food Crops Centre (NNFCC), looking at the production of a selection of major bio-based chemicals from the UK perspective (Mortimer et al., 2009). These workbooks represent the possible production of five major bio-based chemicals consisting of 1,4 butanediol (BDO), acrylic acid, butanol, linear low-density polyethylene (LLDPE) and polylactic acid (PLA) from sugar beet and wheat grain. Biomass conversion and renewable chemical production in these LCA spreadsheet models are based on information derived from the BREW Report (BREW, 2006) which is a comprehensive study prepared under the Growth Program of the European Commission Directorate-General for Research. This study examined different scenarios for the production of a number of different chemicals from different types of biomass, both now and in the future.

The International Organisation for Standardisation (ISO) defines LCA as a “Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 2006:14040). LCA has evolved into a major decision support tool for environmental sustainability assessment related issues, including assessing the emissions reductions of bio-based chemicals in comparison to their fossil sources. However, the quality of the decision support LCA provides is to be determined in terms of its relevance to the type of questions to be answered (Curran, 2012). LCA remains the most reliable method used to verify environmental impacts and support claims. It identifies environmental hot spots in products and materials and establishes the benchmark against which improvements can be measured. Many companies use LCA to demonstrate transparency and corporate credibility to stakeholders and customers. LCA is also used in new product research and development when environmental footprint is important to the future marketing or cost structure of a product. LCA is increasingly recognized in business rationales as consumer and regulatory environmental expectations are increasing in demand and sophistication.

The framework for accounting for the environmental impacts associated with a specified product, process or service is one of the primary considerations when conducting an LCA (ISO 2006:14040; ISO 2006:14044). The first steps in an LCA study involve defining its goal and scope of analysis. This is subsequently followed by the development of a life cycle inventory (LCI), that forms the basis for a life cycle impact assessment (LCIA) and results interpretation. The definition of the system being assessed, and the function of the system are crucial elements of LCA studies. Guidance offered to identify appropriate methodology whilst undertaking LCA for different aims and objectives, distinguishes two different kinds of LCA. These are referred to as 'attributional LCA' and 'consequential LCA'. The two approaches share common features, fundamentally being variations of the same basic methodology and the distinctions between them can be quite subtle (Black et al., 2020). One vital aspect of consequential modelling is that it does not depict the actual process as an attributional model does, but it models the forecasted consequences of decisions. Therefore, consequential LCA is an approach which has been adopted to answer policy questions and anticipating potential future outcomes for biofuels and bio-based chemical environmental analysis (Black et al., 2020).

The Suitability of LCA and its Limitations

It is evident that the first consideration when looking at LCA as a methodology is the question the study is intended to answer. How the question is framed directly influences the boundaries of the LCA and the impact categories that the study is intended to address. For bio-based chemicals, that have been promoted in policies to replace fossil fuels and reduce GHG emissions, having transparent and comparable LCA systems is critical to allow pathways to be compared and assessed against GHG emissions reductions targets and savings. Gnansounou et al. (2009) have reviewed some of the key environmental impact assessment methodologies that have been used to inform biofuels policies and highlight again the need to understand the system definition and boundaries of the methodology, the functional unit and allocation methods used. Singh et al. (2010) identifies the key parameters that influence the outcome of LCAs for lignocellulosic biomass conversion to ethanol as: country; biomass source; system adopted; functional unit; system boundary; land-use change; impact category analysed; sensitivity analysis and reference system. A study by Morales et al. (2015) has reviewed more than 100 case studies of LCAs of lignocellulosic biofuels and reports geographic location, feedstock, functional unit, impact categories, reference system, method of analysis (software used) and allocation. Apart from the methodological issues associated with using LCAs, data availability and data sourcing are also critical parts of the LCA with some data available within LCA software tools. However, more specific outcomes might be achieved for studies using actual data that address a specific feedstock, geographic area, supply chain and conversion plant design. For second generation biofuels, studies have had to rely on simulation studies for conversion plants at scale as, until recently, there has been no commercial scale production.

The suitability of LCA as a technique for assessing GHG emission in accounting for climate change of bio-based chemicals is occasionally challenged (Delucchi 2011, 2013). Normally, this does not necessarily translate into substantial criticisms of the fundamental principles and approaches of LCA itself. These challenges are associated with aspects of consequential LCA, where modelling of indirect land-use change, and vegetation carbon stock changes becomes the subject of debate and influence on the outcome of the LCA. Nonetheless, these difficulties would be an issue to any assessment technique. It follows that the details of LCA calculations and reported results must be specified and carried out so that they are appropriate for addressing the production, consumer, policy, techno-economic, or engineering question which is under consideration. In addition, the results of LCA studies ought to be interpreted with a clear understanding of the research questions originally raised (Matthews et al. 2014).

It is quite evident that there is no single answer to an LCA for a given subject. The result can depend strongly on the way in which the system is defined, and boundary selected. It is very easy, therefore, for different LCA studies to produce a variety of results which sometimes may not necessarily agree. It is unsurprising that results for GHG emissions show a big range that may appear confusing and sometimes contradictory, particularly, with a system as sophisticated as the production and consumption of bio-based chemicals, given many possible sources of feedstocks and unit process stages. However, the most critical issue is to be clear about the goal of the LCA analysis being conducted, i.e., the research question being addressed and to interpret results for LCA in this context (Black et al. 2020).

Land use for crop production driven by increased expectations of future demands for the biomass needed to supply the bioeconomy and a growing, more affluent population, have raised concerns over competition and displacement of current activities, particularly the benefits of replacing fossil fuel-based feedstock. Indirect land use change (ILUC), that is, the unintended expansion of farmland elsewhere globally due to the rededication of existing farmland, may add substantially to the overall environmental impacts of bio-based chemicals and materials (Weiss, et al., 2012). The majority of LCA on bio-based chemicals and materials, does not include ILUC mostly due to the modelling complexity, the uncertainty related to their assessment and the disagreement among experts about how to allocate the resulting impacts. The scientific community agrees that LUC needs to be evaluated within LCA approaches, but the lack of a consistent framework remains a challenge (Sevigné-Itoiz et al., 2021). The treatment of time in LCA by the inclusion of temporal dynamics is another area where guidance is urgently needed. Recent approaches allow the inclusion of time considerations in LCA, but this remains uncommon and is mostly handled on a case-by-case basis. The need to capture time-sensitive indicators such as biogenic carbon flows along the product lifetime is especially relevant for the GHG performance of biomass value chains, and hence, the temporal scope of the study is critical (Sevigné-Itoiz et al., 2021). Furthermore, data usually obtained from LCA inventory databases, is available at global and national level. Using these databases to plan bio-based chemical programs at the regional or local level might lead to under or over-estimating environmental impacts of bio-based chemical product systems (Hosseinzadeh-Bandbafha, et al., 2021).

The lack of a standardized approach for accounting for the biogenic carbon storage in products presents a key challenge to LCA practitioners. The uptake of carbon dioxide (CO_2) from the atmosphere during the photosynthesis process is a unique feature of plant biomass. The transformation of biomass into products represents in effect a removal of CO_2, via its continued storage in the product over a period of time. Bio-based products can thus contribute to reduce the CO_2 level in the atmosphere and address climate change. In LCA, carbon embodied in a product should be considered as a CO_2 reduction or a negative emission. Therefore, it is essential that biogenic carbon flows are assessed in a correct, transparent, and consistent way in LCA. The embedded biogenic carbon is traditionally accounted for in LCA by completely excluding biogenic carbon (known as the 0/0 approach) or giving a value of +1 to biogenic carbon emissions and −1 to carbon uptake (known as the −1/+1 approach) (Navare, et al., 2022). In the currently JRC proposed methodology of the Product Environmental Footprint (PEF) rules addressing biogenic carbon, there is no recognition granted to the producers of biomass-derived products of biogenic

CO_2 removed during photosynthesis and plant growth, compared to fossil ones. In a cradle-to-grave approach, biogenic CO_2 uptake and emissions from disposal are balanced. Therefore, biomass-derived products will not receive any CO_2 burden when they are disposed of, while fossil products will receive a CO_2 burden in case of incineration. However, in a cradle-to-gate life-cycle analysis using PEF methodology, biomass-derived products will not receive any credit for the fact that CO_2 was removed from the atmosphere during photosynthesis and plant growth (Cefic, 2022). Whereas in LCA (ISO 14067, EN 15804 and other LCA standards) biogenic CO_2 uptake in biomass-derived products is addressed by biomass-derived products not receiving any CO_2 burden when they are disposed of, while fossil products receive a CO_2 burden in case of incineration. When the use of the product cannot be singled out, like platform chemicals which are used for a range of different other products or intermediates, the manufacturers need to supply a cradle-to-gate LCA. Accordingly, there is no CO_2 removal credit for bio-based raw materials calculated at the gate of the product (Cefic, 2022). There could be changes in the final PEF when it is finally launched given that JRC is considering recommendations to address these challenges from the chemical industry.

Production Processes & Associated Environmental Impacts

There are multiple biomass-based feedstocks and process routes used in the production of chemicals and materials. Bio-based chemicals and materials are produced from bulk and platform chemicals that act as substrates from which other high-value chemicals and their products are produced (Takkellapati, Li & Gonzalez, 2018). Platform chemicals can be produced in biorefineries from biomass feedstocks.

First Generation Feedstocks to sugars
First generation biomass feedstocks include starch, glucose, and oil crops. Bioethanol is the most widely produce bio-based bulk chemical, widely used in transport fuels, production is dominated by sugar cane production systems in Brazil, and maize based systems in the USA. For ethanol production from corn starch, the first step is milling of the corn to release starch, followed by enzymatic depolymerisation to glucose, which then provides the substrate for fermentation which produces an end-product that includes 10-12% ethanol for the final step of distillation. Sugar cane is crushed to extract sugar juice which provides the substrate for fermentation. An alternative sugar cane route utilises the molasses, a glucose and fructose rich liquid, produced as a co-product during the sugar industries extraction of sucrose.

Second Generation Feedstocks to Sugars
Alternative routes to produce glucose and other sugars utilise lignocellulosic materials such as corn stover, miscanthus, and woody materials. This route requires a pre-treatment phase to access cellulose and hemi-cellulose which are converted to glucose and pentose. However, the techno-economics of pre-treatment technologies are a significant barrier to the growth in use of cellulose feedstocks for bio-based chemicals. Reduced purity of the sugars obtained from lignocellulosic feedstocks is an additional hurdle to the technology.

Third Generation Feedstocks
The third generation of bio-based feedstocks is focussed on marine organisms such as algae.

Biomass-derived platform chemicals and their products are produced via combinations of four types of processes:

i. Mechanical and physical processes that include pre-treatment, milling, pressing, separation, and distillation.
ii. Bio-based chemical processes carried out with enzymes, fermentation with microorganisms, or anaerobic digestion.
iii. Chemical processes including hydrolysis, synthesis, hydrolysis, and oxidation.
iv. Thermochemical processes that use high temperatures and pressures on the biomass including gasification for syngas, hydrothermal upgrading, and syngas (Takkellapati, Li & Gonzalez, 2018).

In this section, a number of bio-based chemical pathways agreed upon by stakeholders during the implementation of the project are presented, focusing on these chemicals' GHG emission savings with respect to their fossil-based counterpart.

Lactic Acid - Through Fermentation for Solvent and Polymer Production

Lactic acid is produced by fermentation of glucose, molasses, or starch. In 2013, the HGCA funded a study to investigate the potential for lactic acid production from UK cereal milling residues, which concluded that although the technology was not sufficiently well developed to use these as a substrate, there was potential for exploring this feedstock for lactic acid production (Arvaniti, et al., 2014). The predominant application of lactic acid is to produce polylactic acid (PLA), although other lactic acid salts, such as lactate esters, can also be derived from it. A preliminary LCA of conceptual lactic acid production from maize stover indicated potential GHG savings of 20% against lactic acid produced via biological valorisation of natural gas (Fei et al., 2020)

Polylactic acid (PLA) is derived from lactic acid. The lactic acid is converted to the lactide dimer then ring-opening polymerisation used to produce polylactide. PLA is a biodegradable polymer that is of interest as a replacement to non-biodegradable polystyrene (PS) (Walker et al., 2022). Due to its biodegradability under industrial composting conditions, PLA is frequently proposed as a promising bio-based matrix for biodegradable products (Operato, et al., 2023).

Walker et al. (2022) undertook UK cradle-to-gate LCA assessment of PLA demonstrating it had a GHG footprint 75% lower than PS. Building on the initial cradle-to gate assessment, prospective modelling considered evolution of future UK energy supplies and end-of-life. The modelling identified that PLA had a higher electricity footprint than PS and therefore GHG emissions were sensitive to how process heat was produced. Combined decarbonisation of electricity supply, heat from hydrogen generated via electrolysis, and landfill for end of life, illustrated a UK route for PLA to achieve a net-negative cradle-to-grave emissions footprint by 2035 (Walker et al., 2022).

In the US, cradle-to-grave LCA assessments for Ingeo's biopolymer drinking cups from maize starch showed a 51% reduction in GHG emissions against conventional polyethylene terephthalate (PET) (PE Americas, 2009).

Table 1: Literature review findings on GHG savings for bio-based lactic acid from fermentation.

Bio-Chemical and/or Pathway	% Change in CO_2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
UK Studies							
Polylactic acid (Maize corn, UK processing)	-75	0.94	3.74	Fossil Polystyrene	Cradle to gate	Global maize feedstocks.	Walker, S. et al. (2022).
Polylactic acid (Sugar beet, UK)	-26 -65 -22	2.154 (Price) 1.019 (Mass) 2.263 (Energy)	2.9	low-density polyethylene (LDPE)	Cradle to gate	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	nnfcc_sb_pla_v13, Benavides, et al., (2020)
Polylactic acid (Wheat Grain, UK)	-24 -80 -43	2.214 (Price) 0.576 (Mass) 1.668 (Energy)	2.9	low-density polyethylene (LDPE)	Cradle to gate	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	nnfcc_wg_pla_v18
Non-UK Studies							
Lactic Acid (Maize Stover, USA)	-20	7.20	8.98	Natural gas (Fei et al., 2020)	Cradle to gate	Corn stover derived L-lactic acid US	Chao Liang, et al. (2023) Fei, Q., et al. (2020).
Non-UK Industry Studies							
Ingeo Biopolymer Drinking Cups (Maize)	-51	2.52	5.2	PET for drinking cup	Cradle-to-grave	Maize to dextrose to lactic acid to lactide to polylactide.	PE Americas (2009)

Ethanol Pathways

In recent years, bioethanol has been produced by fermentation for use as a renewable transport fuel. For context, in 2020 UK domestic production of bioethanol was 114.7 million litres, down from 217 million litres in 2016. According to the DEFRA statistics, bioethanol, and biodiesel production combined required 0.6 – 1.2% of the UK's 5.9 million hectares of cropped area (arable area incl. temporary grassland). However, this is likely an overestimate as currently the UK does not produce ethanol from sugar beet as a primary process. This is produced from the by-products of the sugar refining process. A more reliable figure for 2020 is that 2% of the UK's wheat area was used to supply bioethanol (DEFRA, 2021).

Results from LCA studies indicate that bio-based ethanol production via fermentation of sugarcane, maize, sugar beet, and wheat feedstocks have lower cradle-to-grave GHG emissions than fossil-derived ethanol (Muñoz et al., 2014). GHG emissions from US maize starch and Brazilian sugarcane are 1.60-1.61 kgCO2e / kg of ethanol, representing a 57% saving in GHG emissions against fossil comparators. Low emissions from Brazilian sugar cane cultivation are a function of high yields, but allocation of land use change (LUC) emissions and pre-harvest burning contribute to overall GHG emissions. By comparison US maize feedstocks had higher emissions from cultivation and electricity for processing stages. US maize stover (1.25 kgCO2e/kg) and French wheat (1.27 kgCO2e/kg) have lower emissions, with French wheat having the highest ethanol production emissions of 2.07 kgCO2e / kg. Results of studies on bioethanol are sensitive to both the inclusion of LUC and more so the methodology used to calculate and allocation of LUC emissions.

A hypothetical cradle-to-gate assessment of bioethanol from UK willow lignocellulosic biomass indicated an 88% GHG savings against fossil-derived gasoline (Stephenson et al., 2010). Crucial to the calculated improved GHG emissions was that accounting included combustion of waste lignin for electricity, accounting for carbon sequestration in soils resulting from willow establishment, and carbon embedded in materials. A number of industry and scientific studies also use lignocellulosic bioethanol pathways for different end products including bio-methylene glycol (see section below).

Ethanol can also be produced from lignocellulosic materials by gasification, where the biomass feedstock is pre-treated, subjected to gasification at a high temperature and the resulting syngas is then cleaned. Chemical catalysts or biological fermentation can then be applied to convert the syngas to ethanol.

Ethyl Acetate - via Ethanol for Solvent Applications

Ethyl acetate is produced by several routes, one of which is the esterification of acetic acid and ethanol. These two materials are considered to be bioethanol derivatives produced from biomass. The synthesis of the target product, ethyl acetate, starts with the synthesis of these two raw materials from bioethanol (Hong Thuy et al., 2011).

Table 2: Literature review findings on GHG for bio-ethyl acetate produced via ethanol against fossil comparator.

Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Industry Studies							
Ethyl Acetate	-56	4.32	9.73	Acetic anhydride and fossil ethanol to ethyl acetate	Cradle to gate	Bio-based ethanol feedstock with natural gas use for CHP.	Dunn, J.B., et al. (2015). Bories, C., et al (2018).
Ethyl Acetate			3.0	Acetic acid and fossil ethanol to ethyl acetate	Cradle to gate		Ecoinvent 3.10, 'ethyl acetate production - RER - ethyl acetate', GWP 100 (ISCC 2021), allocation by cut-off
Ethyl acetate	-50		5.0	Acetic acid and fossil ethanol to ethyl acetate	Cradle to grave	Bio-based ethanol with JM ethanol Condensation technology	Crop Energies[245]

[245] Crop Energies, Renewable Ethyl acetate, Information sheet, https://www.cropenergies.com/fileadmin/Resources/CropEnergies/Files/Downloads/Kundenbefragung/Infosheet_-_Ethylacetate_EN.pdf, [accessed 20 Feb 2024]

Ethylene - via Ethanol for Polymer Production

Ethylene is the UK's most widely produced high value chemical (HVC) used in polymers and chemicals. The bulk chemical ethanol can be dehydrated to ethylene, a critically important platform "drop-in" chemical. In 2016, global production of ethylene was 150Mt. The dominant use of ethylene is for polyethylene, a thermoplastic polymer. In 2010 the UK produced an estimated 2.06Mt of ethylene (Griffin et al., 2018). The UK produces 2.5 Mt of primary plastics per year, 5 Mt of converted plastics, and it also imports 5 Mt of primary plastics (Griffin, 2015). The GREET report (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation report) identified that ethylene from bio-based sources can have a GHG saving of 79% when produced from corn stover for a cradle to grave system boundary (Dunn et al., 2015). Similarly, a Dziedziak 2020 study reported -2.39 kgCO_2eq/kg of bio-based ethylene against 1.58 kgCO_2eq/kg of ethylene produced from steam cracking of shale gas, for a cradle to gate system boundary.

Walker et al. (2022) assessed production of high-density polyethylene (HDPE) using UK wheat straw as the feedstock. Bio-based HDPE was the only polymer with a negative emission for cradle-to-gate system boundary based on the current energy system (-2.34 kgCO_2e/kg of polymer compared to 2.23 kg / kg of fossil-HDPE). End-of-life recycling and waste-to-landfill (as opposed to incineration and composting of bio-based polymers) is modelled to result in net-negative cradle-to-grave emissions for the existing energy system.

PET, is commonly used in the production of plastics for food and drinks packaging, and textiles. It is produced from terephthalic acid and monoethylene glycol. Walker et al. (2022) analysis for the UK compared conventional PET with bio-based PET that utilises UK wheat straw derived bio-based MEG. For cradle-to-gate, bio-based PET had 6% higher emissions than fossil fuel PET. Bio-based PET has higher GHG emissions from electricity and heat than fossil PET. Therefore, decarbonisation of the grid and replacing heat from gas with heat from hydrogen generated from electrolysis reduces emissions by proportionally more than fossil PET. Emissions comparisons are sensitive to end-of-life, with bio-based PET emissions profile improved by greater proportions of recycling and landfill, rather than combustion (Walker et al., 2022). In their paper, Walker et al, 2022 argue that emissions related to the end-of-life treatment of a polymer can have two constituent parts, which are process emissions of the treatment and the polymer emissions released at end of life. If a polymer is recycled, process emissions are caused, but emissions from the polymer itself are avoided since the embodied greenhouse gas is not released. Therefore, when comparing bio-based PET to fossil PET with the same end-of-life scenario, the choice of end-of-life treatment becomes a critical factor. In the case of bio-based PET, an improved emissions profile is observed when a greater proportion of the material is subjected to recycling and landfilling or combustion with energy recovery compared to fossil PET.

Industry materials and data releases from global case studies are assertive on the GHG savings on bio-based PE alternatives. Brazilian sugarcane feedstock pathways have the lowest GHG emissions. An industry cradle-to-gate study for Braskem, Brazil indicated negative emissions of -2.15 kgCO_2e/kg of PE, a 217% saving on fossil comparators (E4Tech and LCAWorks, 2015); these industry findings are within the range of potential outcomes identified in equivalent scientific literature (Tsiropoulos et al., 2015).

A hypothetical study on the GHG emissions of utilising lignocellulosic materials from UK willow to produce ethylene glycol for PET in plastic bottles indicate GHG savings of 3% against fossil-based comparators compared to 28% for sugar cane. The lower savings for pathway utilising willow were due to the extra conversion processes required for using lignocellulosic materials (Van Uytvanck et al., 2014).

A hypothetical study of PE production from European wheat straw had lower GHG emissions than the EU first generation crop feedstocks but had the same cradle-to-gate GHG emissions as the fossil fuel comparator. The authors stated that inefficiency of lignocellulosic processing was a limitation for biomass-derived pathways, indicating the Brazilian Braskem plant was an example of high efficiency. However, it should be noted that Braskem utilises sugar cane which is higher efficiency feedstock and also includes emissions credits for when co-products are combusted for electricity (Gursel et al., 2021 & E4Tech and LCAWorks, 2015).

Table 3: Literature review findings on GHG savings for bio-based ethylene from ethanol for polymer production.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Ethylene (Sugarcane, Braskem)	-252%	-2.39	1.58	Stream cracking of ethane from shale gas.	Cradle to gate	Brazilian sugarcane, fermentation route, US production facility.	Dziedziak, 2020.
Polyethylene (Sugarcane, Brazil, Braskem)	-217.5%	-2.15	1.83	Petrochemica l derived polyethylene.	Cradle to gate	Sugarcane fermentation	E4tech, 2013.
UK Studies of Ethylene-based Polymers							
HDPE (Wheat straw, UK)	-205%	-2.34	2.23	Fossil HDPE	Cradle-to-gate	UK wheat straw to high-density polyethylene	Walker et al. 2022.
PET via bio-based MEG (Wheat straw UK)	+6%	2.78	2.62	Fossil PET	Cradle-to-gate	UK wheat straw, pre-treatment and fermentation, dehydration, oxidisation to MEG	Walker et al. 2022.

Monoethylene Glycol - Through Sugar Hydrolysis for Polymer and Surfactant Production

Monoethylene glycol (MEG), aka ethylene glycol, is a di-alcohol used in the production of polyethylene terephthalate (PET). PET is the most widely used thermoplastic polyester in fibres for clothing, containers for food and drink, materials manufacturing, and resins. For MEG, ethanol is first produced via the pre-treatment, mechanical processing, hydrolysis, and fermentation of first or second-generation feedstocks. Ethanol is then distilled and dehydrated to ethylene. Acids or bases along with elevated temperatures are used to catalyse the transformation of ethylene-to-ethylene oxide. Ethylene oxide is then reacted in water to yield MEG.

U.S. based Avantium Renewable Chemistries apply catalytic hydrolysis to convert beet sugars to produce bio-based MEG. Cradle-to-grave LCA indicates an 83% and 57% reduction in GHG emissions against coal- and shale gas-MEG respectively. The main contributor to the improved emissions performance is the use of renewable biomass feedstock.

For second generation feedstocks, UPM, a Scandinavian firm, utilise lignocellulose from industrial wood and residues as feedstock to produce bio-based MEG. Cradle-to-gate LCA studies show a 116% savings on GHG emissions, with a footprint of -0.30 kg CO_2e/ kg of bio-based MEG (Holger, 2023).

Table 4: Literature review findings on GHG savings for bio-based Monoethylene Glycol from sugar hydrolysis.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Industry Studies							
PlantMEG (Sugar beet, Avantium, USA)	-60 -57 -83	0.57	1.41 1.32 3.32	Naptha, Saudi Arabia Shale-Gas, USA Coal, China	Cradle to grave	Ray Technology™ to convert sugar beet to bio-based MEG	Avantium Renewables Chemistries (2022) Third Party and Critically Reviewed Ray plantMEG™ Life Cycle Assessment (LCA)
UPM BioMEG (Wood & residues, Germany)	-116	-0.30	1.85	Fossil MEG Ecoinvent	Cradle-to-gate	Wood residue to bio-based MEG	Holger, J. (2023) UPM Biofore - Beyond Fossils

Methyl Methacrylate - Through Fermentation for Polymer Production.

Fermentation based routes to methyl methacrylate, (MMA) utilizing more sustainable feedstocks represent one potential alternative to petrochemistry. Bio-based routes may provide both long term environmental and economic sustainability. Given the competitiveness of the market, the development of bio-based polymethylmethacrylate (PMMA) has become a priority of many of the current producers (Lebeau, et al., 2020). Previous work on the conversion of sugar to MA or MMA using engineered biocatalysts has focused on the evaluation or development of one of several pathways, ranging from the direct production of methacrylic acid (MA) to the combined use of biochemical and traditional chemistry to produce MA from glucose. Adeoye, et al., 2023 studied the impacts of implementing some of these principles on the production of MMA, the monomer of PMMA popularly known as acrylic glass. This study used life cycle assessment (LCA) methodology to compare the potential environmental impacts of three different approaches to the production of MMA. Two of these are established industrial pathways: the acetocyanohydrinprocess (ACH-MMA) and the AlphaLuciteprocess (AL-MMA), which represent the conventional and a fast-rising industrial route, respectively, while the third, the *in situ* formaldehydeprocess (inFAL-MMA) is a lab-based process. The scenarios were evaluated using the ReCiPe2016 impact assessment methods. The results obtained highlighted some hot spots that can benefit from process improvements and careful material and energy source selection. It also confirmed the importance of different factors like data quality, degree of process optimization, energy source, and others on the results that can be obtained in a LCA. The results of AL-MMA compared with both the ecoinvent and carbon minds scenarios of ACH-MMA were 8.74, 7.12 and 5.41 kg CO2 eq/kg MMA respectively (Adeoye, et al., 2023). Iyer and Kelly (2021) MMA fossil pathway developed for GREET model suggest a GWP of 9.2 kg CO2 eq/kg MMA, whereas Cefic, 2014 has a lower figure for the production of fossil MMA at 3.47 kg CO2 eq/kg MMA. Evidently, there is some GWP savings when using the MMA fossil counterfactual from GREET as indicated in the Adeoye, et al., 2023 study compared to using the Cefic, 2014 counterfactual. It has to be emphasized that pathways which do not offer significant GHG reduction, are unlikely to be commercialised by industry stakeholders.

Table 5: Literature review findings on GHG savings for Bio-based MMA from fermentation.

Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Bio-based MMA	i) -5 ii) -23 iii) -42	i) 8.74 ii) 7.12 iii) 5.41	9.2	Iyer & Kelly	Cradle to gate	i) Acetocyanohydrin process ii) AlphaLucite process iii) Formaldehyde process	Adeoye et al., 2023
Bio-based MMA	-	-	3.47	Cefic, 2014	Cradle to gate	-	-

Methanol - From Green Hydrogen and CO_2 Off Gas.

Methanol is an essential chemical building block and emerging energy resource. Methanol can be synthesized using a mixture of hydrogen, carbon dioxide, and carbon monoxide. These elements can be derived from a variety of feedstocks and processes (thermochemical and biochemical), with conventional methanol produced from natural gas or coal (Subudhi, et al., 2023). Syngas and biogas have been acknowledged as potential resources for methanol synthesis. Renewable methanol is a low carbon liquid chemical and fuel produced from sustainable biomass, often called bio-based methanol, or from captured carbon dioxide and hydrogen produced from renewable electricity, referred to as e-methanol. Proman announced they are set to start producing e-methanol alongside UK port operator (Global Energy Group). They are currently developing a renewable power to methanol plant to utilise local sources of captured carbon dioxide to be located at the Nigg Oil Terminal in the Highlands of Scotland. The plant is scheduled to come into operation from 2026 (MI, 2023).

Studies from Canada and the USA indicate that utilising hydrogen produced from renewables for e-methanol delivers negative cradle-to-gate emissions, and cradle-to-grave emissions are 82% lower than methanol produced via natural gas (Zang et al., 2021 & Khojasteh-Salkuyeh, 2021).

Another study of the Stenungstund chemical industry cluster in Sweden demonstration biomass gasification of forest resources have shown 81% saving in GHG emissions against fossil methanol (Røyne, Ringström, and Berlin, 2015).

More broadly, Sternberg et al. (2017) analysis highlighted that net GHG savings and the case for chemical production from H_2 and CO_2 are not just chemical specific but also sensitive to the efficiency of the fossil-based approach they replace. For example, GHG savings are material with comparison to syngas by steam-methane reforming, but not syngas production by combined reforming.

Table 6: Literature review findings on GHG savings for methanol from green hydrogen and CO2 off gas.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
e-Methanol (H2 from wind and solar and CO2, USA)	-161 -85	(kgCO2e/MJ methanol) -55.7 13.6	(kgCO2e/MJ methanol) 91.5	Natural gas reforming	i) Cradle to gate ii) Cradle to grave	Captured CO_2 as feedstock. Hydrogen from wind and solar	Zang, G., Sun, P., Elgowainy, A. and Wang, M., 2021.
e-Methanol (CO2 hydrogenation, Canada)	-60	0.2	0.5	Natural gas reforming	Cradle to gate	Feedstock mixture of CO2 from flue gas and hydrogen from water hydrolysis	Khojasteh-Salkuyeh, Y., Ashrafi, O., Mostafavi, E. and Navarri, P., 2021.
e-Methanol (CO2 hydrogenation, Quebec, Canada)	-300	-1.2	0.6	Natural gas reforming	Cradle to gate	Feedstock mixture of CO2 from flue gas and hydrogen from water hydrolysis	Khojasteh-Salkuyeh, Y., Ashrafi, O., Mostafavi, E. and Navarri, P., 2021.
e-Methanol (CO2 hydrogenation, global)	-95	0.1	2.1	Natural gas reforming	Cradle to grave	Feedstock mixture of CO2 from flue gas and hydrogen from water hydrolysis	Methanol Institute, Carbon footprint of methanol.

Butanol, Acetone, and Ethanol Through ABE Fermentation for Solvent Applications

Biological production of butanol under anaerobic conditions is typically referred to in literature as a part of 'ABE fermentation', since acetone, butanol and ethanol are usually produced simultaneously in this process (Birgen, et al., 2019). However, large-scale fermentative production of butanol still suffers from high substrate cost and low product titres and selectivity. There have been great advances in the last few decades to tackle these problems. Nevertheless, understanding the fermentation process variables and their interconnectedness with a holistic view of the current scientific state-of-the-art is still largely lacking (Birgen, et al., 2019). The main uses for butanol are as a solvent and applications in plasticisers. Through strain evaluation, Green Biologics Ltd (GBL) had identified biocatalysts that exceed the performance of traditional commercial ABE strains, especially with respect to solvent ratio, where GBL production strains have butanol ratios that are more than the 60% of the solvent mix seen with culture collection strains such as *C. acetobutylicum* (Davies, 2013). The ABE pathway also produces significant quantities of acetone and ethanol. In LCA, these are treated as co-products and upstream emissions and energy use are allocated to them.

Wu et al. (2007) looked at the GHG emissions associated with producing butanol from maize for transport fuel via the ABE pathway. The study built upon existing modelling of emissions for transport fuels concluding that well-to-wheel GHG emissions from biomass-derived butanol could offer modest

GHG savings against gasoline comparators (8-32%). Variation in GHG savings reflected treatment of the co-product acetone greater GHG savings when bio-based acetone awarded credits for displacing fossil-acetone. Where co-product acetone was credited with energy allocation the GHG benefits of butanol against gasoline was largely negated. Building on Wu et al. (2007) work by Desta, Lee and Wu (2021) evaluated the use of maize corn and maize stover to produce ABE transport fuel. Well-to-tank studies indicated that ABE could have GHG savings of 58% for corn stover and 53% for corn feedstock per MJ compared with gasoline and diesel (Desta, Lee & Wu, 2021). A cradle to gate LCA study conducted by Mortimer et al., 2009 on bio-based butanol produced from UK sugar beet via ABE process achieved 88% (1.575 kg eq. CO_2/kg) GHG savings against fossil-based butanol, whereas bio-based butanol produced from wheat achieved a 97% (0.078 kg eq. CO_2/kg) when mass allocation of upstream emissions was applied. These results are based on a plant with a natural gas fired CHP unit providing process heat and electricity with its surplus electricity sold to the grid. A higher GHG saving can potentially be achieved by using a renewable energy source for CHP unit such as biomethane (Appendix A and B).

Prospective work on utilizing cyanobacteria that excrete biobutanol indicated that genetically engineered strains could improve the environmental impact of the production system, through higher productivity. However, the high energy demand of the cultivation and harvesting steps outweighed productivity improvements, and overall emissions were 20% higher than the fossil reference (Villacreses-Freire, Ketzer & Rösch, 2021). Renewable energy and improved genetic engineering were identified as crucial to achieving positive environmental outcomes against fossil comparators.

Table 7: Literature review findings on GHG savings for ABE from fermentation.

Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Acetone, Butanol & Ethanol (ABE) (Maize corn, USA)	-53%	44.34 g CO_2e / MJ of ABE	not available	not available	Well to tank	US corn, fermentation, heat and power demand met by biomass burning, excess electricity is exported and credited. DDGS for animal feed.	Desta, M., Lee,T. Wu,H. (2021)
Acetone, Butanol & Ethanol (ABE) (Maize stover, USA)	-58%	15.63 g CO_2e / MJ of ABE	not available	not available	Well to tank	US corn, pre-treatment of corn stover with enzymes before anaerobic fermentation, heat and power demand met by biomass burning, excess electricity is exported and credited.	Desta, M., Lee,T. Wu,H. (2021)
Butanol (Maize, USA)	-8% to -32%	not available	not available	not available	Well to wheel	US maize production, processing, hydrolysis, fermentation and gas stripping, downstream processing	Wu, M., Wang, M., Liu, J., Huo, H. (2007).
UK Industry Data							
Celtic Renewables* i) Acetone ii n-Butanol iii) Ethanol	i) -74% ii) -69% iii) -63%	kgCO2e/kg dry i) 1.21 ii) 1.40 iii) 1.13	kgCO2e/kg dry i) 4.59 ii) 4.58 iii) 3.03	Fossil	Cradle to gate	Whiskey distillery residues and waste potatoes	Celtic Renewables (13th October, 2021) Summary of ERM's Carbon Footprint Assessment

Biosurfactant - Through Fermentation for Solvent Applications

In the emerging biotechnology industry, biosurfactants have become attractive microbial products due to their advantages over synthetic surfactants in terms of environmental sustainability, global public health, and the concerns of industries to produce environmentally friendly goods. The amphipathic structure of biosurfactants with hydrophilic and hydrophobic moieties enable these molecules to play a key role in emulsification, foam formation, detergency, and oil dispersion activities, which are desirable traits in different industries such as the pharmaceutical and cosmetic industries (Sarubbo, et al., 2022). Fats and waste oils can be bio-transformed to glycolipid biosurfactants. Their triglycerides, consisting of fatty acids, can be used as precursors by several microorganisms or as initial reactants in lipase-catalyzed processes for biosurfactants' production. Microbial biosurfactants are amphiphilic molecules, comprised of both hydrophilic and hydrophobic moieties, that can reduce surface and interfacial tension. Several bacteria produce them as a key mechanism to facilitate hydrocarbon uptake through micelle solubilization or pseudosolubilization (Kopsahelis, et al., 2018). In their study, Kopsahelis, et al. 2018 identified that among the biosurfactant production processes, sophorolipids production resulted in 22.7% higher environmental impact compared with rhamnolipids. Similarly, fatty acid ethyl esters (FAEE) production can be classified as a more environment- friendly process compared with monoglycerides (MAG), resulting in 67% lower environmental impact based on the environmental indicators assessed. The increased thermal requirements of the MAG production phase is the main contributor to their negative environmental performance, with the overall energy consumption for MAG production being 3-fold higher than for the FAEE formation phase (Kopsahelis, et al., 2018). Alcohol ethoxylates surfactants are produced via ethoxylation of fatty alcohol (FA) with ethylene oxide. The source of FA could be either palm kernel oil (PKO) or petrochemicals. Shar et al., 2016 study compared the potential environmental impacts for PKO-derived FA (PKO-FA) and petrochemicals-derived FA (petro-FA). The results showed that petro-FA has overall lower average greenhouse gas (GHG) emissions (~2.97 kg CO_2e) compared to PKO-FA (~5.27 kg CO_2e). The study indicated that the judicious decisions on land use change, effluent treatment and solid waste treatment are key to making PKO-FA environmentally sustainable.

Elias, et al., 2021 performed simulations considering the implementation of two process layouts integrated to an existing plant of 1G ethanol in Brazil. The two processes proposed for Biosurfactant production from Sugarcane Bagasse yielded GWP of 9.55 and 17.10 kg eq. CO2/kg respectively, significantly higher than the chosen fossil comparator. The GWP for the reportable precursors ranges from – 1.989 kg CO2e /kg for Coconut Oil Methyl Ester to 4.894 kg CO2e/kg for 3-dimethylaminopropylamine (DMAPA). For the final surfactants, the range is from – 0.887 kg CO2e/kg for cocamide diethanolamine (CDEA) to 2.674 kg CO2e/kg for C12–C15 triethanolamine esterquat (Schowanek, et al., 2018). There is a significant difference between the cradle-to-gate GWP of the renewable pre-cursors palm oil/palm kernel oil (PO/PKO) and coconut oil (CNO). The CNO products have a calculated net negative cradle-to-gate GWP, while the PO/PKO products have a net positive GWP. The latter is mainly attributable to the land use change (LUC) factor and plantings on peat soils. Beef tallow also has a net negative GWP of − 1529 kg CO2e/tonne. This value is very sensitive to the allocation choice. Preliminary LCA results for a study conducted by Holiferm UK show a 50% GHG saving against fossil and partially fossil-based (PKO) counterfactuals.

Table 8: Literature review findings for biosurfactant through fermentation.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Bio-Surfactant (Sugarcane bagasse, BR)	+681%	17.10	2.19	Petrochemical ethoxylated alcohol *Lapuente Díaz de Otazu et al., 2021	Cradle to grave	Production of sophorolipid BSs from sugarcane bagasse using processes that are integrated within a lignocellulosic sugarcane-to-ethanol biorefinery.	Elias, et al. 2021.
Bio-based Surfactant (Sugarcane bagasse, BR) * Hot water pretreatment	+336%	9.55	2.19	Petrochemical ethoxylated alcohol *Lapuente Díaz de Otazu et al., 2021	Cradle to grave	Hot water bagasse pre-treatment and ultrafiltration for BS recovery.	Elias, et al, 2021.
Bio-based Surfactant (Palm kernel oil (PKO)	+77%	5.27	2.97	petrochemicals-derived fatty alcohol (FA) (petro-FA)	Cradle to gate	Alcohol ethoxylates surfactants produced via ethoxylation of fatty alcohol from PKO.	Shar et al., 2016
UK Industry Studies							
Bio-based surfactants (Rapeseed, corn, Holiferm, UK)	-50%	1.3	2.6	Naphtha/PKO FAME	Cradle to gate	Rapeseed Oil, Glucose	Holiferm, 2023.

Furandicarboxylic Acid - (and HMF) Through Sugar Chemistry for Surfactant and Polymer Production

Plant sugars, including fructose, can be catalysed to Furandicarboxylic acid (FDCA), the building block for polyethylene furandicarboxylate (PEF). PEF is a bio-based alternative to fossil PET, where FDCA replaces the fossil-based building block chemical purified terephthalic acid (PTA). One production route utilises maize for catalytic conversion of starch via hydrolysis and enzymes to dextrose and water, then isomerization to dextrose and fructose. The study used simulation based on experimental data finding a 49% saving in GHG emissions against fossil comparators (Eerhart et al., 2012).

Avantium's YXY® Technology PEF-based bottles utilise wheat starch but could in future be produced from cellulose in second generation biomass feedstocks. Here FDCA is polymerised with plant-based MEG to make PEF. PEF is of interest to the packaging sector due to its enhanced barrier, structural, and recycling properties. Full cradle-to-grave assessment of Avantium's PEF LCA properties identified a 62% reduction in cradle-to-grave GHG emissions compared with a fossil-PET, using the function unit of a 250 mL bottle (Plum et al., 2023). The study identified that the barrier properties of PEF, allowed for more lightweight design and reduced material usage.

Table 9: Literature review findings for Furandicarboxylic acid through sugar chemistry.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Furandicarboxylic acid* (Corn stover)	NA	8 - 9	NA	*Terephthalic acid (PTA)	Cradle to gate	Maize corn stover hydrolysed to sugar and then catalytically converted to 5-hydroxymethyl furfural; 5-hydroxymethyl furfural is converted to FDCA through catalytic oxidation.	Chao Liang, Ulises R. Gracida-Alvarez, Troy R. Hawkins, and Jennifer B. Dunn 2023
Non-UK Industry Data							
PEF (Avantium XYX® Technology)	62%	NA	NA	PET bottle	Cradle to grave	Starch from European wheat to make FDCA, which is polymerised with plant based MEG.	Plum et al., 2023

1,4 Butanediol - through Fermentation for Polymer Production

1,4-butanediol (1,4-BDO) is an important tetracarbon diol. As a platform chemical, it can be converted to various chemicals, including tetrahydrofuran, γ-butyrolactone, polybutylene terephthalate, and polybutylene succinate, which are widely used in fields ranging from medical, food, light industry to chemicals and materials. 1,4-BDO as one of the co-monomers in the polyesters that has been applied to produce a variety of promising bio-based plastic materials such as polybutylene adipate terephthalate (PBAT). The petroleum based chemical synthesis method is the main route to produce 1,4-BDO but faces several issues such as non-renewability of raw materials, severe environmental pollution, and complicated catalysis conditions. An alternative route for the green and sustainable production of 1,4-BDO is by biomass conversion through engineered microbial cell factories to alleviate the problems suffered by the fossil route (Guo, et al., 2022). Lignocellulosic routes to 1,4-BDO indicate reduced GHG emissions compared to fossil comparators in the range of 36 – 66% (Di Bari et al., 2020 & Forte et al., 2016).

Walker et al., (2022) in their LCA paper compared fossil and bio-based polymers based on being identical or with very similar properties. They assumed that the polymers were manufactured in the UK using methods and feedstock common or most suitable for the UK, including their end-of-life treatment processes. The fossil based Low-density polyethylene (LDPE) is formed from the polymerisation, using a high pressure free radical polymerisation process, with ethylene produced from the cracking of naphtha refined from crude oil. Poly(butylene adipate-co-terephthalate) (PBAT) is made from the copolymerisation of 1,4 butanediol, adipic acid and terephthalic acid. It provides a potential biodegradable substitute to low-density polyethylene (LDPE), widely used in packaging. Cradle-to-gate assessment by Walker et al. (2022) calculated that the PBAT had a higher carbon footprint of 4.2 $kgCO_2/kg$ compared for 2.41 $kgCO2_2$ / kg of polymer for LDPE. They observed that the lowest emission case achieved for PBAT is when processing heat was produced by hydrogen from electrolysis, with end-of-life treatment scenario given by 2.7% composting and 97.3% landfill. Under no future decarbonisation pathway by 2040 did PBAT have lower emissions than LDPE (Walker et al., 2022).

Table 10: Literature review findings for butanediol through fermentation.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Butanediol (1,4-)* (Bio-based succinic acid)	-66%	1.31	3.8	Natural gas via methanol	Cradle to grave	Hydrogenation of bio-based succinic acid (with ethanol)	Adom, F., Dunn, J.B., Han, J. and Sather, N., (2014).
Butanediol (1,4-)* (Caedoon lignocelluose)	-36%	2.82	4.4	Fossil-based BDO from Natural gas	Cradle to gate	Enzymatic Hydrolysis of biomass - caedoon lignocellulosic biomass	De Bari, I.; Giuliano, A.; Petrone, M.T.; Stoppiello, G.; Fatta, V.; Giardi, C.; Razza, F.; Novelli, A. (2020)
Butanediol (1,4-) (Wheat straw, IT)	-64%	1.60	4.4	Fossil-based BDO from Natural gas	Cradle to gate	Italian wheat straw hydrolysis and fermentation, with CHP from unconverted soils.	Forte, Annachiara, Amalia Zucaro, Riccardo Basosi, and Angelo Fierro. (2016).

Succinic Acid - through Fermentation for Polymer Production.

Bio-based succinic acid (Bio-SA) is one of the high value bio-based chemicals that more than a decade ago was identified as a compound that has the potential to improve the profitability and productivity of biorefineries. This is in-line with facilitating the transition from fossil-based industrial chemistry to sustainable bio-based production (Patel et al., 2018). SA is usually made by the catalytic hydrogenation of petrochemically-derived maleic acid or maleic anhydride. In 2010, several companies began to produce first-generation Bio-based SA in various locations across the world, including Reverdia (Italy), Bio-based Amber (France & Sardinia), Myriant (US) and Succinity (BASF/Corbian Purac collaboration in Spain). However, by 2018 falling oil prices rendered bio-based succinic acid uncompetitive with fossil-based alternatives with these companies and sites either closing or being sold and repurposed for other bio-based products (Denny, 2022). Bio-based SA can be used as a precursor to 1,4-butanediol by a hydrogenation route. It can also be used to replace adipic acid in polyester polyols (for polyurethanes), saturated polyester resins or replace isophthalic acid to make PET polymer among other uses (Cok, et al., 2014). Production with maize stover is indicated to lead to GHG reductions against fossil fuel comparators (Cok et al., 2014).

Table 11: Literature reviewing findings for bio-based succinic acid through fermentation.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Succinic Acid (1,4-) (Corn stover residues)	i) -30% ii) -85% iii) -24%	1.36	i) 1.94 ii) 8.82 iii) 1.78	i) fossil succinic acid ii) adipic acid iii) maleic anhydride	Cradle to gate	Corn stover & Succinic acid recovery via LLE (extraction of purified chemical from fermentation broth via liquid-liquid extraction method)	Cok B, Tsiropoulos I, Roes AL and Patel MK. (2014).
Succinic Acid (1,4-) (Corn stover residues)	i) -5% ii) -79% iii) -4%	1.85	i) 1.94 ii) 8.82 iii) 1.78	i) fossil succinic acid ii) adipic acid iii) maleic anhydride	Cradle to gate	Corn stover & succinic acid recovery via EDI (extraction of chemical from fermentation broth via electrode ionization)	Cok B, Tsiropoulos I, Roes AL and Patel MK, (2014).

Dihydrolevoglucosenone - through Sugar Chemistry as a Novel Solvent.

The use of bio-based solvent dihydrolevoglucosenone (Cyrene) is to replace fossil derived solvents such as DMF and NMP. Cyrene, derived from sawdust via the Furacell process, has physicochemical properties comparable to typically used fossil-derived polar aprotic solvents. It does not have any of the same carcinogenic, mutagenic or reproductive toxicity issues as its fossil fuel derived counterpart (Arif, et al., 2023). The environmental assessment carried out by Arif, et al., 2023 adopted a cradle-to-gate perspective and assessed three endpoint impact categories: Human health, Ecosystems and Resources. This study looked into the application of Cyrene for membrane fabrication. Despite lower environmental impacts for producing bio-based renewable solvents, using such solvents to fabricate membranes displayed a higher environmental impact score in all endpoint categories. This discrepancy was attributed to the lower yield of the membrane fabrication process when using bio-based solvents. This indicated that further work is needed to optimise membrane fabrication so that the benefits of using bio-based solvents can be maximised. The bio-based synthesis normalised impact scores were 256 %, 135 % and 227 % higher for human health, ecosystems and resources, respectively compared to fossil counterpart (Arif, et al., 2023). Circa Group comparative LCA study on the production of bio-based Cyrene verses fossil DMF as a counterfactual commissioned by Merck, yielded 1.4 kgCO2 eq./kg Cyrene compared to 10.7 kgCO2 eq./kg Cyrene, which is a potential GWP savings of approximately 87% (Circa, 2023). Circa Group are building their first-of-a-kind 1000 mtpa plant in France with the goal of 80,000 mtpa global offtake capacity by 2030, including in Asia, the Americas and Europe. The Circa Group process can use any homogeneous waste cellulosic feedstock such as sawdust, sugarcane bagasse etc.

Bio-based Propane from Sustainable Aviation Fuel (SAF) Production as Feedstock for Crackers (Ethylene, Propylene etc).

Conventionally, LPG consists of propane and/or butane, which are typically produced as a by-product of crude oil refining and natural gas processing. Bio-based propane (or bioLPG) is the term commonly used to describe LPG that is derived from biomass, which is chemically largely identical to the fossil-based LPG. There are several biomass conversion processes in which bio-based propane is produced as a coproduct and there is a plethora of biomass feedstocks that can be used in those processes. These range from the hydrotreating of vegetable oil to produce HVO bio-based diesel to the production of synthetic fuels through gasification and synthesis. Currently, the primary production route for bio-based propane is as a co-product of HVO bio-based diesel where the process yields are in the range of 5-8% (Hopwood, et al., 2019). Due to the large amounts of HVO bio-based diesel produced significant volumes of bio-based propane can be obtained, despite the yields being low (Johnson, 2017). There are also a small number of novel processes whereby bio-based propane can be produced as the main target product. These include the use of specialised microbes to ferment organic wastes to produce bio-based propane (rather than bio-based methane), and the direct synthesis of propane from the syngas produced from the gasification of woody bio-based mass (Hopwood, et al., 2019). A stronger focus on advanced processes, using wastes and lignocellulosic feedstocks, which typically achieve greater efficiencies and deliver greater GHG savings can be expected. As a result of future growth demands, development of such facilities is increasing and an increase in production and availability of bio-based propane can therefore be expected. HVO bio-based propane's carbon footprint varies, depending on the feedstock and the four variables (allocation method, methane capture at the oil mill (or not), application of indirect land-use change (or not), and classification of the feedstock as a residue (or not)), from as low as 5 g CO_2e/MJ to as high as 102 g. In most cases, this qualifies for government support, i.e., financial credits and biofuel mandates enacted by EU member states under the Renewable Energy Directive (Johnson, 2017). Bio-based propane production from anaerobic digestion of biogenic fraction of MSW gives a carbon footprint ranging from -500 to 80 g CO_2e/MJ.

Table 12: Literature review findings for bio-based-propane from SAF.

Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis.	Fossil Comparator	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Bio-based Propane (MSW)		gCO2e/MJ -500 to +80	gCO2e/MJ 76.0	LPG	Cradle to gate	bio-based- or municipal solid waste	WLPGA (2023) Carbon Intensities, Renewable and Fossil Liquid Gases, LPG & DME
Hydrotreating (HVO) Natural oils/fats		gCO2e/MJ 5 to 102	gCO2e/MJ 76.0	LPG	Cradle to gate	Hydrogenating vegetable or animal oil/fat	Johnson, 2017
Hydrotreating (HVO) Used Cooking Oil (USA)		gCO2e/MJ 21	gCO2e/MJ 76.0	LPG	Cradle to gate	Hydrogenating Used Cooking Oil	Baldwin, et al., 2022
Gasification with Fisher Tropsch		gCO2e/MJ 5 to 17	gCO2e/MJ 76.0	LPG	Gradle to gate	Gasification with Fisher Tropsch of woody biomass	WLPGA (2023) Carbon Intensities, Renewable and Fossil Liquid Gases, LPG & DME
Gasification with Fisher Tropsch (with CCS)		gCO2e/MJ -95 to -105	gCO2e/MJ 76.0	LPG	Gradle to gate	Gasification with Fisher Tropsch of woody biomass (with CCS)	WLPGA (2023) Carbon Intensities, Renewable and Fossil Liquid Gases, LPG & DME

Bio-based Naphtha from SAF Production as Feedstock for Crackers (Ethylene, Propylene etc).

Bio-based naphtha has been available on the market for a few years now. In Europe, about 150,000 tonnes are already used annually, mainly for polymer production. Bio-based naphtha differs only slightly from fossil-based naphtha in their chemical composition (Nova, 2021). To drive the transformation of the chemical industry towards renewable feedstocks quickly and on a large scale, innovative new and sustainable renewable sources of naphtha from bio-based materials are important. As the production capacity of renewable diesel (RD) and sustainable aviation fuel (SAF) grows, so will the output of the hydrotreated vegetable oil (HVO) process co-products, including bio-based naphtha and bio-based propane. As with petro-based, bio-based naphtha can be used as a feedstock to make ethylene, propylene, and butadiene for chemicals and plastics. Neste performed a cradle-to-gate Life Cycle Assessment (LCA) to produce renewable hydrocarbons for use as cracker feed via the NEXBTL process, including potential greenhouse gas (GHG) emissions released by the products at the end-of-life, to assess its environmental impacts (Plum, et. Al., 2023). Fossil naphtha was used as a fossil reference to the renewable liquid hydrocarbons. Naphtha is the most representative fossil reference product in this context since the renewable hydrocarbons can be used to substitute fossil naphtha in a steam cracker. Animal fat waste used cooking oil and various wastes and residues from vegetable oils processing represent the top three largest waste and residue raw material categories in the order of their current and estimated shares of Neste's total annual renewable raw material inputs for their bionaphtha production. Neste sources wastes and residues globally for bio-based refineries located in Finland, the Netherlands and Singapore (Plum, et. Al., 2023). cradle-to-gate system boundary was used with a functional unit of 1 kg of bio-based naphtha. For the Neste renewable liquid hydrocarbons, the net GWP (including the emission of the biogenic carbon contained in the product at the End-of-Life as CO2) resulted in 0.45 kg CO2 eq./kg of product. Compared to fossil naphtha (3.44 kg CO2 eq./kg of product), the Neste renewable liquid hydrocarbons have at least 85% lower GWP. The lower GWP of the renewable liquid hydrocarbons can be largely attributed to the biogenic removals from CO2 uptake during biomass growth and the subsequent biogenic emissions during the life cycle steps and end-of-life (Plum, et. Al., 2023).

Table 13: Literature review findings for bio-based Naphtha from SAF production.

bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Non-UK Studies							
Naphtha (Vegetable oils)	-76%	0.79	3.313	Fossil derived	Cradle to gate	Vegetable oils derived	Feiferytė, A., Dvarionienė, J. and Gumbytė, M., 2015.

Acetic Acid, Biomethane and Methanol.

Biomethane, produced from waste-derived biomass, can be used as a replacement for natural gas in the production of acetic acid. Acetic acid is produced by the steam reforming of natural gas to syngas for use in methanol carbonylation. Methanol carbonylation involves reacting methanol with carbon monoxide from syngas in the presence of a metal carbonyl catalyst (Budsberg, et al., 2020). There are several routes for producing ethyl acetate. Ethyl acetate can be produced via esterification of ethanol and acetic acid. It can also be produced by reacting acetic acid with ethylene, a common practice in the United Kingdom.

Methyl acetate is produced by catalytic esterification of acetic acid and methanol with sulfuric acid as a catalyst in a batch reactor. It has wide applications in the production of solvents, perfumes, surfactants, and surface-active agents (Kusuma, et al., 2021).

Biomethane can be produced via the "bio-based gas route", including the anaerobic digestion of bio-based waste with upgrading of the bio-based gas, to reduce CO_2 and increase CH_4 concentrations. By comparison, the "syngas route", uses gasification of dry or semi-wet biomass, followed by cleaning, conditioning, methanation, and upgrading to syngas (Ardolino and Areana, 2019). The syngas route is still at a demonstration level.

Assessment of methanol production using forest resources for the Stenungsund chemical industry cluster in Sweden gave cradle-to-gate LCA data for two production routes. Gasification of wood biomass to methanol with co-production of electricity delivers emissions of 0.54 $kgCO_2e/kg$ of methanol, whilst production of methanol via pulp mill off-gases resulted in emissions of 0.35 $kgCO_2e/kg$. Both approaches deliver net GHG reductions against fossil comparator (Røyne, F., Ringström, E. and Berlin, J., 2015).

More early-stage approaches include dry reforming of methane (DRM) from food/agricultural waste combined with CO_2 utilisation to produce syngas. This syngas is then further treated and converted to methanol. The decarbonisation of process occurs through two-mechanisms. One, the utilisation of captured CO_2 as feedstock, and two, the syngas reaction to methanol can be carried out thermally or in a plasma environment. Neither route is considered industrially mature, and both are unfavourable thermodynamically (Matin-Espejo et al., 2022). Cradle-to-gate work by Delikonstantis et al. 2021 estimate emissions to be 2.82 $kgCO_2e/kg$ of methanol via the non-direct thermocatalytic route using bio-based gas feedstock, compared to a fossil comparator of 2.08 $kgCO_2e/kg$ of methanol. The bio-direct route utilises non-thermal plasma, an enabling green technology, had emissions of 7.46 $kgCO_2e/kg$ of methanol.

The INEOS Acetyls business at Saltend in Hull is the largest producer of acetic acid, acetic anhydride and ethyl acetate in Europe. Ineos use an efficient and low carbon Cativa™ process for the production of acetic acid. The Cativa™ process uses an iridium catalyst package to promote the carbonylation of methanol resulting in an acetic acid. The Ineos Saltend site produces acetic acid with emissions of 1.2 $kgCO_2e/kg$.

Table 14: Literature review findings for bio-based methane production to acetic acid, acetic anhydride, and ethyl acetate.

Bio-based Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	Bio-based Pathway	Citation
Methanol (Plasma using biomass feedstock)	+81%	7.46	4.12		Cradle to grave	PBGG - plasma assisted process, bio-based gas feedstock	Delikonstantis, et al., 2021.
Methanol (Dry thermocatalytic using biomass)	+52%	2.82	1.86		Cradle to grave	TBG - thermocatalytic process, bio-based gas feedstock, energy from natural gas	Delikonstantis, et al. 2021
Methanol (Biomass gasification)	-152%	-0.54	1.03	Natural Gas	Cradle to gate	Biomass Gasification with electricity as co-product (credited)	Røyne, F., Ringström, E. and Berlin, J., 2015.
Methanol (Pulp mill off gases)	-66%	0.35	1.03	Natural Gas	Cradle to gate	KRAFT pulp mill stripper off gases	Røyne, F., Ringström, E. and Berlin, J., 2015.
Acetic acid (China)	-	-	4	Coal	Cradle to gate		Presentation Sustainability – INEOS Acetyls Europe May 2023
Acetic acid (Europe)	-	-	1.4	-	Cradle to gate		Presentation Sustainability – INEOS Acetyls Europe May 2023
Acetic acid (Ineos Hull)	-	-	1.2	Natural Gas	Cradle to gate	Cativa®XL technology	Presentation Sustainability – INEOS Acetyls Europe May 2023
Acetic acid (derived from biomethane and fossil methanol displacing natural gas	-80%	0.24	1.2	Natural Gas	Cradle to grave	Biomethane derived syngas and formylation of methanol	NNFCC calculation

UK Findings based on North Energy Associates Updated Models

The North Energy Associates models developed in 2009, were updated with emission factors, fertiliser inputs and GWP (IPCC, 2023), to evaluate selected bio-based chemical production in the UK, with UK specific data for wheat and sugar beet feedstock cultivation and harvesting, transportation and processing. The default values used in the models reflect UK farming practice, including the updated current fertiliser application rates and crop yields (Nix, J., 2023 and BSF, 2022), typical transportation modes and distances, and primary energy and GHG emissions factors for fuels and grid electricity

(DUKES, 2023). These Excel models represent “cradle-to-gate” system boundary which covers all stages of the bio-based chemical production chain including cultivation, harvesting, processing of feedstock, conversion and purification, transportation, and waste disposal and treatment (Mortimer et al., 2009). The use and end-of-life phases of the bio-based chemicals are not taken into consideration. These models include allocation step for all upstream emissions to co-products based on allocation procedures by economic value, energy content, mass and substitution credits reflected in the results (see Appendix A and B). Due to the lack of clear guidance over allocation procedures, the excel models include the facility to generate results using all the main options of allocation.

In these models, the source of heat and electricity consists of using a natural gas-fired CHP unit with any surplus electricity being exported to the grid. The potential of using bio-based methane CHP unit in the future has also been tested by substituting the Natural gas with bio-based methane, whilst assuming the CHP with same specifications as a natural gas-fired unit (see results in Appendix A). Nonetheless, these Excel models do not account for direct land use change (dLUC) and indirect land use change (iLUC) due to lack of reliable data and limitations with global land use modelling. It was assumed that all the other data in the models would not have changed significantly since the original models were developed.

The key steps in the processing of the sugar beet considered in these models are washing, shredding and diffusion to give thin juice, and purification and concentration to provide a thick juice. This provides fermentable sugar for subsequent bio-based chemical production. The co-products are pulp from diffusion assumed to be used mainly for animal feed, and Limex as a soil improver from purification. The steps to wheat grain processing consist of milling and hydrolysis prior to fermentation and conversion to bio-based chemicals. The co-product is distillers’ dark grains (DDGS), mainly for animal feed production (Mortimer et al., 2009). The results (see Appendix A and B) demonstrate a number of GHG savings across the bio-based chemicals depending on the allocation measures applied, but also on the type of fuel used for the CHP plant. Under the accounting rules, CO2 emissions associated with using bio-based methane in a CHP plant is considered biogenic. The reason for this is that biogenic carbon is assumed to fixed within the renewable chemicals and, therefore, given amounts of carbon dioxide have been removed from the atmosphere.

Contextualizing the Environmental Assessment

Renewable resources of biological origin offer the UK chemical industry an opportunity to diversify its feedstocks and to produce bio-based chemical products. This will help modernize and strengthen the UK’s industrial base, creating new greener value chains and potentially cost-effective industrial processes, whilst safeguarding the environment.

Increasing sustainable biochemical production ambition within the UK chemical industry is a prerequisite for society to remain below the 1.5°C limit of global temperature rise, as well as work towards climate neutrality by 2050 and reduce dependence on fossil-based products. However, there remains no consensus within the chemical industry on the need to transition fully away from fossil fuel use for chemical production.

The development of bio-based chemicals and materials will help the UK accelerate progress towards a low-carbon economy. This can occur through the displacement of fossil feedstocks; storage and management of biological carbon flows embedded in materials and products; and the potential to enhance domestic terrestrial carbon stocks (Ni et al., 2020).

Most of the LCA studies reviewed for bio-based chemicals and materials indicated potential net GHG savings against fossil comparators. However, the often-higher energy requirements for bio-based feedstock processing demonstrate how GHG emission savings evolve over time and are dependent upon decarbonisation of heat and electricity supply but the opportunity for emission reduction is greater than fossil fuel base production. For GHG management the key production stages for bio-based chemicals are feedstock production, heat and electricity requirement during processing, and consideration to end-of-life options.

The GHG emissions of biomass feedstock production varies, determined by biomass yield, fertiliser application rate, and attribution of land use change. In this stage, GHG emissions are highly sensitive to accounting for indirect land-use changes (iLUC). iLUC accounts for the change in land use and associated carbon emissions, that is deemed to occur when an increase demand and market prices for bio-based feedstocks increase land conversion. However, modelling and attribution of iLUC is highly uncertain and contested. Therefore, policy decisions around bio-based feedstocks should actively consider management of risks from iLUC and be sensitive that numerical estimates of iLUC from bio-based chemical production are often a function of the modelling assumptions. This can be extrapolated to biomass feedstock supply for bio-based chemical production. The focus in the UK context ought not to be on more first generation feestock production, but rather on repurposing the ethanol feedstock.

Domestically, integration of lignocellulosic feedstocks such as miscanthus with annual cropping systems can enhance soil carbon stocks (Ni et al., 2020), whilst woody crops such as short-rotation coppice and willow with also enhance temporary carbon storage in biomass (Climate Change Committee, 2019). These lignocellulosic feedstocks can also be utilised by the industry for bio-based chemical production.

In 2020 the UK utilised 0.6% of its cropland area (incl. temporary grassland) for wheat and sugar beet production for biofuels. 71% of crop-derived bio-based ethanol for the UK was imported, with the United States, Ukraine, Brazil, and France as the largest suppliers.

Allowing for the electrification of the transport fleet, UK gross demand for biofuels is likely to reduce in the medium to longer-term, potentially releasing feedstock that can be diverted to the UK chemicals industry.

Evaluating the utilisation of bio-based feedstocks for transport fuels or renewable chemicals is not a like-for-like comparison. Renewable transport fuels are combusted upon use whilst bio-based chemical and materials end-of-life can be a variety of different routes. Bio-based material and chemicals have the potential to temporarily store carbon out of the atmosphere over a time period either in long term use (e.g., construction), through recycling in a circular economy or in curated landfill.

Bio-based chemical processing has significant potential for sustainability process optimization through learning from doing in commercial plants, alongside GHG emissions reduction through decarbonisation of UK heat supply, away from natural gas. This both reduces emissions and creates a pathway to net-negative polymers such as bio-based PET, PLA, and bio-based HDPE (Walker et al., 2022). Walker et al. (2022) modelled heat decarbonisation via transition to hydrogen produced from electrolysis. Hydrogen fuel switching is the major decarbonisation lever INEOS plan to implement for their acetyl operations in Hull (INEOS, 2023).

End-of-life treatment is relevant, as biodegradable chemicals are often claimed to be CO_2 emission neutral, but methane emissions from landfilling without energy recovery can have an impact on the neutrality benefits. Polymers have continued to offer a unique combination of low cost and high durability for numerous applications. Depending on energy and end-of-life scenarios chosen their work suggests that polymers with net negative emissions can be manufactured from 2025, dependent upon higher composting and landfill rates, and reduced incineration (Walker et al., 2022).

LCA is a standardized and widely used tool to measure related progress by quantifying environmental sustainability performance of chemical products along their life cycles. In this study, we have reviewed LCA studies applied to produce bio-based chemicals through several pathways such as microbial fermentation. These reviewed studies show that inconsistent application of well-defined LCA guidelines can yields highly variable results even when the same impact categories are assessed. Despite this, the existing evidence base is instructive.

There is large variation in considered GWP impact and life cycle stages across LCA studies, reflecting current challenges when assessing bio-based materials and bio-based chemicals. Each individual studied system can be unique in features and components, which renders it difficult to compare with functionally equivalent systems or processes. However, this is a well-known problem in LCA, and not unique to bio-based chemicals but also applies to many other product systems. Most of the papers that have been reviewed in this study have taken the conventional LCA approach which is static without temporal and spatial variations. However, systematic analysis of spatiotemporal dynamic variations and comprehensive operable dynamic models are still lacking in LCA. The importance of considering the significance of biomass provision not only for bio-based chemicals but also for energy and their GHG emissions accounting with respect to national inventory is outlined in in the section 7.1 to 7.2.

Bio-based Chemicals Versus Bioenergy GHG Savings

It is evident that biomass feedstocks represent an abundant carbon neutral renewable resource to produce both bio-based energy and bio-based materials, and its enhanced use would address several societal needs and the global agenda to attain net-zero by 2050 (Ragauskas, et al., 2006). State of the art manufacturing systems for converting biomass to valuable fuels and bio-based chemicals in a biorefinery set up is being realised, thanks to advances in biotechnology, process chemistry, and engineering. The integration of agroenergy crops and biorefinery manufacturing technologies offers the potential for the development of sustainable bio-based power and bio-based materials that will lead to a new manufacturing paradigm.

A systematic framework developed by Huang, et al., 2021 was used to quantitatively analyse the mitigation potential of 25 large-volume and promising platform bio-based chemicals. To properly account for the energy requirements of producing different bio-based chemicals, they constructed material and energy balances of a biorefinery and develop simulation and optimization models to calculate the energy needed to separate and purify these bio-based chemicals. Their study showed that biomass-based production can lead to significant GHG mitigation. Under the most conservative assumptions (i.e., 25% conversion and high separation energy), bio-based chemicals can reduce GHG emissions by up to 88%. Under the most optimistic assumptions (i.e., 75% conversion and easy separation), the emission reductions can be as great as 94% (Huang, et al., 2021).

Posen et al., 2014 examined the GHG implications of a more flexible policy based on Renewable Fuel Standard (RFS2) in the USA, which includes credits for chemical use of bio-based ethanol to produce bio-based ethylene. A Monte Carlo simulation was employed to estimate the GWP of conventional low-density polyethylene (LDPE), made from natural gas derived ethane (mean: 1.8 kg CO_2e/kg LDPE). The GWP from bio-based ethanol and bio-based LDPE were examined for three biomass feedstocks:

U.S. corn (mean: 0.04 kg CO2e/kg bio-based ethanol and 2.6 kg CO2e/kg LDPE), U.S. switchgrass (mean: −0.0007g CO2e/kg bioethanol and −2.9 kg CO2e/kg LDPE), and Brazilian sugar cane (mean: 0.0012kg CO2e/kg bio-based ethanol and −1.3 kg CO2e/kg LDPE. Results suggest that U.S. production, bioethanol achieves slightly greater GHG reductions than bio-based LDPE. For imported Brazilian products, bio-based LDPE achieves greater GHG reductions than bio-based ethanol (Posen et al., 2014).

Evidently, both bioenergy and bio-based chemicals contribute to reducing GHG emissions, but their specific applications and challenges vary. As we strive for a net-zero UK, balancing energy needs with environmental considerations remains crucial. While converting biomass to bioenergy is somewhat simpler, bio-based chemical offers sustainability and high-value chemicals as demonstrated in this report. Integrating both approaches could lead to better process efficiency and a circular economy. Biochemicals that do not degrade and are landfilled sequester biogenic carbon permanently. Incinerated biochemicals release biogenic carbon to the atmosphere. The uptake of biogenic carbon into the bio-based chemical feedstocks offsets these combustion emissions, which are then often considered carbon neutral, especially if the feedstock has a brief planting-to-harvest time window. Biochemicals that enter supply chains with high recycling rates contribute to a circular economy because their biogenic carbon is circulated in the production–use–recycling loop. Renewable fuels in the UK fuel supply achieved an aggregated GHG saving of 82% compared to fossil fuels. Accounting for emissions from indirect land-use change (ILUC) reduces this GHG saving to 78% (RTFO, 2023). Of the 32.8 million litres eq. of verified renewable fuel produced from UK origin feedstock, the most common by feedstock and fuel type combination was bioethanol from wheat i.e., 13.6 million litres, 42% of renewable fuel from UK origin feedstock (RTFO, 2023). Bioethanol produced in the UK with wheat as feedstock achieved GHG savings of 73% (excluding ILUC) and 62% when ILUC was considered. We estimate that a tonne of wheat produces approximately 149 kg CO2/tonne of wheat, which validates the 150 kg CO2/tonne of wheat found in literature Greenhouse gas emissions profile for 1 tonne of wheat produced in Central Zone (East) New South Wales (Brock, et al., 2012). We used data from OFGEM to estimate GHG emissions savings for using solid biomass for electricity generation in the UK. We estimated that 98% GHG savings can potentially be achieved per tonne of biomass (willow, wheat straw and miscanthus). However, the carbon sequestration potential of bio-based chemicals at the end of life increases the importance of utilizing biomass to convert into chemicals rather than burning it for energy purposes (Walker et al., 2022). Therefore, the results demonstrate that there potential GHG savings benefits achieved for using biomass for producing biofuel for the transport industry and for electricity as can be made in using the same resource to produce bio-based chemicals.

Implications for National GHG Inventory

For UK Industry and policymakers, it important to consider how bio-based chemicals and bio-based polymers will be accounted for in the UK's national GHG inventory, the capacity of the inventory to capture GHG benefits of bio-based chemical and carbon flows, as the inventory is the basis for the UK's Net Zero Target for 2050.

The UK National GHG Inventory follows the IPCC Guidelines (IPCC, 2006 & IPCC, 2019). The treatment of biofuels and wood biomass for energy, provides a starting point for the consideration of bio-based chemical supply chains in the national inventory. For biofuels and wood biomass for energy, the CO_2 emissions from the combustion of biogenic carbon are treated in the Agriculture, Forestry, and Other Land Use (AFOLU) sector for the country of harvest. For the country of energy use, this CO_2 should be reported as a separate inventory item, considered “Outside of Scope”. It is important that countries assess biofuel origin so as to separate out fossil- and biogenic-feedstock, as this avoids double-counting and over-reporting of CO_2 emissions. The same principal would have to be applied to the treatment of the end-of-life of bio-based chemicals and polymers in the Waste sector, to separate bio and fossil-feedstock based polymers and chemicals. N_2O and CH_4 emissions are calculated at point of combustion for biofuels and not in the AFOLU sector, so there is no risk of double accounting in Waste. however, appropriate emissions factors would be required for end-of-life stream for bio-based polymers and chemicals.

The international nature of bio-based chemical feedstock and product supply chains also require consideration for the UK’s GHG inventory. Where biomass feedstocks for bio-based chemical production are imported to the UK to substitute domestic fossil-chemical processing and consumption, energy consumption and emissions could potentially increase as the energy requirements for bio-based chemical production are higher. The impact of the biogenic-carbon embedded in the feedstock, would potentially be captured in the Waste sector if accounting was capable of differentiating biogenic and fossil-carbon based polymers, and credit bio-based polymers. Where biomass feedstock is imported to the UK, for the UK to process final products that are then exported and consumed elsewhere, biogenic carbon sinks would potentially have to be accounted for as exported.

This is an area that requires more detailed consideration, and expertise in emissions accounting for Waste associated with bio-based chemicals within the national GHG inventory.

Conclusions

A search of the peer review literature and other published sources was undertaken to determine what the GWP impact of bio-based chemicals was, compared to the fossil-derived equivalent chemicals. Most of the results obtained in literature are based on a cradle-to-gate system boundaries, but a few are for cradle-to-grave. There are significant limitations to applying LCA, identified across the LCA literature, and outlined in this report. The accuracy of LCA study depend on the quality and availability of relevant data. It was impossible to conduct a bottom-up assessment for lack of data from stakeholder chemical companies given its proprietary nature. Estimations and inclusion or exclusion of ‘biogenic carbon’ claims in LCA studies, has significant influence on results. There is still no clear consensus in literature on dealing with this aspect with respect to impact assessment.

The bio-based chemical industry has huge potential for producing chemicals and materials with a reduced GWP impact; compared to a functionally equivalent fossil resource. The GWP impact is dependent upon such factors as GHG emissions associated with the agronomy, or forestry practices and accounting for a potential land use change. End-of-life fate is a critical consideration. Many LCA studies report on the manufacture stage of the life cycle only (the cradle to factory gate stage). However, any consideration of the GWP benefits of using different chemicals and materials ought to take account of the entire life cycle and as such, the results are heavily dependent upon the assumptions made especially on the end-of-life stages. It can be estimated from the reviewed literature conducted for this study that bio-based polylactic acid produced from fermentation of wheat, corn and sugar beet has a GHG saving ranging from 22% to 80%. Similarly, GHG saving ranging from 205% to 252% could potentially be achieved by producing bio-based ethylene from ethanol produced from biomass. Bio-based MEG produced from sugar beet and lignocellulosic feedstocks had a GHG saving between 32% and 116%. The highest savings of

116% arise from using lignocellulosic material. For bio-based Methyl methacrylate produced via fermentation process demonstrated a GHG emission saving ranging from 5% to 42%. A range of 8% to 74% GHG emission saving was evident for the production of Acetone, Butanol and Ethanol via ABE fermentation. Furandicarboxylic acid produced by Avantium using their XYX technology with starch from European wheat had a 62% GHG emission savings, whereas 1,4 butanediol had a range of 36% to 66% depending on the system boundary chosen. For bio-based succinic acid GHG savings ranged from 24% to 92% depending on the fossil comparator used and the technology used for extracting chemical from the fermentation broth. Bio-based propane had a GHG emissions saving ranging from -35% to 758% depending on the bio-based pathway and the feedstock, whereas bio-based Naphtha had a saving of 76%. Bio-based methanol produced via biomass gasification had a saving of 66% to 156% for cradle to gate system boundary. Table 15 gives a summary of the UK bio-based chemical GHG emissions saving in comparison to fossil-based counterfactual.

When analysing the potential for the use of feedstock chemicals for bio-based chemical production, it is necessary to consider the constrained availability of land placing limits on total production, a major consideration in a UK context. However, with the possible phase out of the internal combustion engines and being replaced by electric vehicles, a significant proportion of feedstock could potentially be dedicated to produce bio-based chemicals. Net negative polymers that sequester carbon are feasible via combination of decarbonisation of electricity supply, alternative heat sources and improvements in end-of-life away from combustion. Bio-based PET, PLA, and HDPE can achieve this as widely reported in the reviewed literature.

The potential for the production and use of bio-based chemicals and materials as a climate change mitigation strategy in the UK is evidenced from literature. Based upon the currently available literature LCA data, there is a case to be made for stating that there are potential benefits to be obtained by the substitution of a bio-based chemicals for a functionally equivalent fossil-derived chemicals. There is potential for the use of bio-based ethanol as a feedstock for ethylene production, but the economics must be favourable.

In terms of transferability the findings in this report support and demonstrate that UK has the right kind of feedstock and potential to produce bio-based chemicals and bio-based materials. Complete value chains rather than single bio-based based chemical products should be analysed together to understand the interactions across sectors and land uses with the goal of identifying opportunities where collective benefits can be realized.

Table 15: Target bio-based chemicals GHG emissions saving compared to fossil-based chemicals.

Chemical	Bio-based GHG Emissions (kgCO2e / kg of bio-based product)	Fossil Comparator GHG Emissions (kgCO2e / kg of product)	GHG savings (kgCO2e / kg of product)	GHG saving %	Notes
Lactic Acid (or as PLA)					
Lactic acid from MSW	1.99	4.43	2.44	**55%**	UK data used obtained from Fiberight. Fiberight utilises MSW as feedstock to produce bio-based LA assumed to displace synthetic LA.
Wheat Grain	0.58	2.9	2.32	**80%**	Lactic acid as PLA produced from UK wheat grain assumed to displace fossil-based polyethylene, calculated from the North Energy Associates Ltd models.
Monoethylene glycol (direct from sugar)	-0.3	1.85	2.15	**116%**	Bio-based MEG produced from forest residues as feedstock.
Ethyl Acetate (via ethanol)	2.5	5	2.5	**50%**	Bio-based Ethyl acetate produced using JM bio-based ethanol condensation technology
Ethylene (via ethanol)					
HDPE (Wheat straw)	-2.34	2.23	5.41	**243%**	Wheat straw as the feedstock. Bio-based ethylene assumed to displace fossil-based Ethylene.
Wheat grain	1.59	4.5	2.91	**65%**	Ethylene produced from UK wheat grain assumed to displace fossil-based ethylene, calculated from the North Energy Associates Ltd models.
Sugar beet	1.26	4.5	3.24	**72%**	Ethylene produced from UK sugar beet assumed to displace fossil-based ethylene, calculated from the North Energy Associates Ltd models

Lignocellulose (wheat straw)	0.27	4.5	4.23	**94%**	Ethylene produced from UK wheat straw assumed to displace fossil-based ethylene, calculated from the North Energy Associates Ltd models
Methyl methacrylate	9.1	10.3	1.2	**12%**	Bio-based MMA. LCA non-UK data obtained from literature source
Methanol (from CO2)	0.1	2.1	2	**95%**	CO2 from point source emissions feedstock and hydrogen from water hydrolysis using wind energy. We were not able to obtain UK data, hence this data is based on global data from the Methanol Institute.
Butanol (Acetone/Ethanol)					
Whiskey residues	1.4	4.58	3.18	**69%**	Bio-based butanol produced from UK whiskey residues as a feedstock. Assumed to displace fossil-based butanol. Functional unit used is per tonne of biomass feedstock.
Sugar beet	1.58	2.45	0.87	**36%**	Butanol produced from UK sugar beet assumed to displace fossil-based butanol, calculated from the North Energy Associates Ltd models with mass allocation.
Wheat grain	0.08	2.45	2.37	**97%**	Butanol produced from UK wheat grain assumed to displace fossil-based butanol, calculated from the North Energy Associates Ltd models with mass allocation.
Biosurfactant					
Rapeseed/corn starch	1.3	2.6	1.3	**50%**	Rapeseed/corn starch as a feedstock. Displaces fossil-based Naphtha
Furandicarboxylic acid	2.52	3.48	0.96	**28%**	Bio-based FDCA produced from wood chips as feedstock at a lab scale obtained from literature.
1,4-Butanediol					

Wheat grain	1.85	3.8	1.95	**51%**	1,4-Butanediol produced from UK wheat grain assumed to displace fossil-based 1,4-Butanediol, calculated from the North Energy Associates Ltd models
Sugar beet	2.79	3.8	1.01	**27%**	1,4-Butanediol produced from UK sugar beet assumed to displace fossil-based 1,4-Butanediol, calculated from the North Energy Associates Ltd models
Lignocellulose (Caedoon)	2.82	4.4	1.58	**36%**	Literature data for bio-based 1,4-Butanediol produced from Lignocellulose (Caedoon) assumed to displace fossil-based 1,4-Butanediol
Succinic acid					
Wheat grain	2.72	4.96	2.24	**45%**	SA produced from UK wheat grain assumed to displace fossil-based Succinic acid, calculated from the North Energy Associates Ltd models.
Sugar beet	2.95	4.96	2.01	**41%**	SA produced from UK sugar beet assumed to displace fossil-based Succinic acid, calculated from the North Energy Associates Ltd models.
Lignocellulose (corn stover)	1.48	7.89	6.41	**81%**	Bio-based SA assumed to displace fossil-based SA. No wheat straw production of Bio-based SA was found in literature for the UK. The reference used assumed extraction of purified chemical from fermentation broth via liquid-liquid extraction method.
Dihydrolevoglucosenone	1.4	10.7	9.3	**87%**	Bio-based Dihydrolevoglucosenone from forestry residue as a feedstock. Not UK data, but product can potentially be produced in the UK using UK lignocellulosic feedstock.
Acetic acid (47% bio-based)	0.24	1.2	0.96	**80%**	Calculated based on displacement of natural gas used as feedstock with biomethane.

Note: Target chemicals that were not possible to find for the UK, we have used literature data assuming feedstock could be substituted for those available in the UK.

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Appendices

Appendix A: List of carbon footprint and GHG savings for selected bio-based chemicals produced from North Energy Associates Ltd Excel Models using a Natural gas fired CHP plant.

Renewable Chemical	Model Used	Default Case Summary	Allocation Procedure	Total GHG Emissions (kg eq. CO_2/kg)	Fossil Comparator (kg eq. CO_2/kg)	Percentage CO2 eq Saving (%)
Butanol from sugar beet	nnfcc_sb_bu_v23	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	4.578 1.575 4.912 24.335	2.450	-87 88 -101
Butanol from wheat grain	nnfcc_wg_bu_v12	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	2.943 0.078 3.081 1.156	2.450	-20 97 -26
Polyethylene from sugar beet	nnfcc_sb_lldpe_v27	CHP, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	-0.728 -1.528 -0.821 11.409	2.310	132 166 136
Polyethylene from wheat grain	nnfcc_wg_lldpe_v36	CHP, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	-0.113 -1.197 -0.736 1.541	2.310	105 152 131
Polylactic acid from sugar beet	nnfcc_sb_pla_v13	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	2.154 1.019 2.263 7.253	2.310	7 56 2
Polylactic acid from wheat grain	nnfcc_wg_pla_v18	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	2.214 0.576 1.668 1.999	2.310	4 75 28
1,4 butanediol from sugar beet	nnfcc_sb_bdo_v17	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	2.790 3.044 2.765 7.598	3.800	27 20 27
1,4 butanediol from wheat grain	nnfcc_wg_bdo_v37	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price Mass Energy Substitution	2.420 1.888 1.846 2.266	3.800	36 50 51

Appendix B: List of carbon footprint and GHG savings for selected bio-based chemicals produced from North Energy Associates Ltd Excel Models using Biomethane fired CHP plant.

Renewable Chemical	Model Used	Default Case Summary	Allocation Procedure	Total GHG Emissions (kg eq. CO_2/kg)	Fossil Comparator (kg eq. CO_2/kg)	Percentage CO2 eq Saving
Butanol from sugar beet	nnfcc_sb_bu_v24	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price	-0.385	2.450	116
			Mass	-1.238		150
			Energy	-0.365		115
			Substitution	-1.164		
Butanol from wheat grain	nnfcc_wg_bu_v13	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price	-0.073	2.450	103
			Mass	-1.582		165
			Energy	-0.409		117
			Substitution	-4.327		
Polyethylene from sugar beet	nnfcc_sb_lldpe_v28	CHP, CHP steam for animal feed drying, fixed carbon	Price	-2.270	2.310	198
			Mass	-2.643		214
			Energy	-2.330		201
			Substitution	-1.028		
Polyethylene from wheat grain	nnfcc_wg_lldpe_v37	CHP, CHP steam for animal feed drying, fixed carbon	Price	-0.617	2.310	127
			Mass	-2.031		188
			Energy	-1.625		170
			Substitution	0.132		
Polylactic acid from sugar beet	nnfcc_sb_pla_v14	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price	-0.385	2.310	117
			Mass	-0.856		137
			Energy	-0.309		113
			Substitution	0.424		
Polylactic acid from wheat grain	nnfcc_wg_pla_v19	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price	-0.022	2.310	101
			Mass	-1.001		143
			Energy	-0.530		123
			Substitution	-0.473		
1,4 butanediol from sugar beet	nnfcc_sb_bdo_v18	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price	-0.253	3.800	107
			Mass	-0.087		102
			Energy	-0.229		106
			Substitution	0.508		
1,4 butanediol from wheat grain	nnfcc_wg_bdo_v38	CHP, Waste solids to energy recovery, CHP steam for animal feed drying, fixed carbon	Price	0.120	3.800	97
			Mass	-0.381		110
			Energy	-0.418		111
			Substitution	-0.257		

Appendix C: GHG emissions for pathway bio-based chemicals and fossil comparators identified in the academic literature.

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
1	Acetone, Butanol & Ethanol (ABE) (Maize corn, USA)	53%	44.34 g CO2e / MJ of ABE		Gasoline	Well-to-tank	No	US production of corn, fermentation, heat and power demand met by biomass burning, excess electricity is exported and credited. DDGS for animal feed.	Desta, M., Lee,T. Wu,H. (2021) Well-to-wheel analysis of energy use and greenhouse gas emissions of acetone-butanol-ethanol from corn and corn stover. Renewable Energy,Volume 170, Pages 72-80,ISSN 0960-1481.
2	Acetone, Butanol & Ethanol (ABE) (Maize stover, USA)	58%	15.63 g CO2e per MJ		Gasoline	Well-to-tank	No	US production of corn, pre-treatment of corn stover with enzymes before anaerobic fermentation, heat and power demand met by biomass burning, excess electricity is exported and credited.	Desta, M., Lee,T. Wu,H. (2021) Well-to-wheel analysis of energy use and greenhouse gas emissions of acetone-butanol-ethanol from corn and corn stover. Renewable Energy,Volume 170, Pages 72-80,ISSN 0960-1481.
3	Acetic acid (Popular, USA using ethyl acetate)	0% to 150%	1.0 *to* 2.5	1	Petroleum based acetic acid	Cradle to gate	No	Popular biomass growth and harvest, pre-treatment and hydrolysis followed by fermentation with acetogens, distillation uses ethyl acetate to extract acetic acid from water to extract acetic acid. Energy comes from co-firing natural gas with lignocellulose OR natural gas and lignocellulose exported.	Budsberg, E., Morales-Vera, R., Crawford, J.T. et al. Production routes to bio-acetic acid: life cycle assessment. Biotechnol Biofuels 13, 154 (2020).
4	Acetic acid (Popular, USA using alamine and diisobutyl)	-137% to -82%	"-0.37 *to* 0.18	1	Petroleum based acetic acid	Cradle to gate	No	Popular biomass, pre-treatment and hydrolysis followed by fermentation with acetogens, distillation uses alamine and diisobutyl ketone solvent to extract acetic acid. Energy comes from co-firing natural gas with lignocellulose OR natural gas and lignocellulose exported.	Budsberg, E., Morales-Vera, R., Crawford, J.T. et al. Production routes to bio-acetic acid: life cycle assessment. Biotechnol Biofuels 13, 154 (2020).
5	Acetic Acid (from e-Methanol)	-58%	0.4176	1	*Budsberg et al., 2020 fossil comparator	Cradle-to-grave	No	Mentanol from hydrolysis with renewables, and natural gas from shale.	Adom, Felix and Jennifer Dunn. (2015) Material and Energy Flows in the Production of Macro and Micronutrients.
6	Acetone (Waste gas feedstocks)	-170%	-1.78	2.55		Cradle to gate	No	Gas fermentation	Liew, F.E., Nogle, R., Abdalla, T. et al. Carbon-negative production of acetone and isopropanol by gas fermentation at industrial pilot scale. Nat Biotechnol 40, 335–344 (2022).

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
7	Butanediol (1,4-)* (Bio succinic acid)	-66%	1.31	3.8	Natural gas via methanol	Cradle to grave	No	Hydrogenation of bio succinic acid (with ethanol)	Adom, F., Dunn, J.B., Han, J. and Sather, N., 2014. Life-cycle fossil energy consumption and greenhouse gas emissions of bioderived chemicals and their conventional counterparts. Environmental science & technology, 48(24), pp.14624-14631.
8	Butanediol (1,4-)* (Caedoon lignocelluose)	-36%	2.82	4.4	Natural gas	Cradle to gate	No	Enzymatic Hydrolysis of biomass - caedoon lignocellulosic biomass	De Bari, I.; Giuliano, A.; Petrone, M.T.; Stoppiello, G.; Fatta, V.; Giardi, C.; Razza, F.; Novelli, A. From Cardoon Lignocellulosic Biomass to Bio-1,4 Butanediol: An Integrated Biorefinery Model. Processes 2020, 8, 1585.
9	Butanediol (1,4-) (Wheat straw, IT)	-64%	1.60	4.4	Natural gas	Cradle to gate	No	Italian wheat straw hydrolysis and fermentation, with CHP from unconverted soils.	Forte, Annachiara, Amalia Zucaro, Riccardo Basosi, and Angelo Fierro. 2016. "LCA of 1,4-Butanediol Produced via Direct Fermentation of Sugars from Wheat Straw Feedstock within a Territorial Biorefinery" Materials 9, no. 7: 563.
10	Butanol (Maize, USA)	-8 to -32%			Gasoline	Well-to-wheel	No	US maize production, processing, hydrolysis, fermentation and gas stripping, downstream processing	Wu, M., Wang, M., Liu, J., Huo, H. (2007). Life-Cycle Assessment of Corn-Based Butanol as a Potential Transportation Fuel. 10.2172/925379.
11	Butanol (n-)* (Cyanobacteria)	27%	3.10	2.45	Fossil	Cradle to gate	No	Butanol production from Cyanobacteria	Villacreses-Freire, D., Ketzer, F. & Rösch, C. Advanced Metabolic Engineering Approaches and Renewable Energy to Improve Environmental Benefits of Algal Biofuels: LCA of Large-scale Biobutanol Production with Cyanobacteria Synechocystis PCC6803. Bioenerg. Res. 15, 1515–1530 (2022).
12	Caprolactone (Corn stover, USA)	-48%	1.56	3	Hydrogenation of fossil derived benzene	Cradle to gate	No	Enzymatic Hydrolysis of biomass - maize stover	Thaore, V., Chadwick, D., Shah, N. (2018) Sustainable production of chemical intermediates for nylon manufacture: A techno-economic analysis for renewable production of caprolactone, Chemical Engineering Research and Design, Volume 135, Pages 140-152,ISSN 0263-8762,
13	Ethanol (Sugar cane, BR)	-57%	1.60	3.74	Hydration of ethylene in Europe	Cradle to grave	Yes	Sugar cane production Brazil, fermentation to ethanol	Muñoz, I., Flury, K., Jungbluth, N. et al. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19, 109–119 (2014).
14	Ethanol (Maize corn, USA)	-57%	1.60	3.74	Hydration of ethylene in Europe	Cradle to gate	Yes	Maize grain production USA, fermentation to ethanol	Muñoz, I., Flury, K., Jungbluth, N. et al. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19, 109–119 (2014).

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
15	Ethanol (Maize stover, USA)	-67%	1.25	3.74	Hydration of ethylene in Europe	Cradle to gate	Yes	Maize stover production USA, fermentation to ethanol	Muñoz, I., Flury, K., Jungbluth, N. et al. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19, 109–119 (2014).
16	Ethanol (Sugar beet, FR)	-66%	1.27	3.74	Hydration of ethylene in Europe	Cradle to grave	Yes	Sugar beet production France, fermentation to ethanol	Muñoz, I., Flury, K., Jungbluth, N. et al. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19, 109–119 (2014).
17	Ethanol (Wheat, FR)	-45%	2.07	3.74	Hydration of ethylene in Europe	Cradle to grave	Yes	Wheat production in France, fermentation to ethanol	Muñoz, I., Flury, K., Jungbluth, N. et al. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int J Life Cycle Assess 19, 109–119 (2014).
18	Ethanol (Willow, UK)	-88%	0.27	2.26	Fossil derived gasoline	Cradle to gate	No	Willow production UK, hydrolysis and fermentation, wastes including lignin send for combustion for electricity generation. Includes C sequestration in soils and woody biomass.	A.L. Stephenson, P. Dupree, S.A. Scott, J.S. Dennis. The environmental and economic sustainability of potential bioethanol from willow in the UK,vBioresource Technology, Volume 101, Issue 24, 2010, Pages 9612-9623, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2010.07.104.
19	Ethyl Acetate	-56%	4.32	9.73	Acetic anhydride and fossil ethanol to ethyl acetate	Cradle to gate	No	Bio-based ethanol feedstock with natural gas use for CHP.	"Dunn, J.B., Adom, F., Sather, N., Han, J., Snyder, S., He, C., Gong, J., Yue, D. and You, F., 2015. Life-cycle analysis of bioproducts and their conventional counterparts in GREET (No. ANL/ESD-14/9 Rev.). Argonne National Lab.(ANL), Argonne, IL (United States). Bories, C., Guzman Barrera, N.I., Peydecastaing, J., Etxeberria, I., Vedrenne, E., Garcia, C.V., Thiebaud-Roux, S. and Sablayrolles, C., 2018. LCA case study: comparison between independent and coproduction pathways for the production of ethyl and n-butyl acetates. The International Journal of Life Cycle Assessment, 23, pp.251-266."
20	Ethylene (Sugarcane, Braskem)	-252%	-2.39	1.58	Stream cracking of natural or shale gas	Cradle to gate	Yes	Brazilian sugarcane, fermentation route, US production facility.	Dziedziak, C., 2020. Life Cycle Assessment (LCA) for Sustainable Chemical and Polymer Production, A techno-economic investigation commissioned by the members of the Carbon Dioxide Capture and Conversion (CO2CC) Program, The Catalyst Group Resources (TCGR), https://www.catalystgrp.com/wp-content/uploads/2020/11/BRIEF-CO2CC-2020-RPT1-LCA-for-Sustainable-Chemical-and-Polymer-Production.pdf.

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
21	Polyethylene (Sugarcane, Brazil, Braskem)	-217.5%	-2.15	1.83	Petrochemical derived polyethylene.	Cradle to gate			
22	HDPE (Wheat straw, UK)	-205%	-2.34	2.23	Fossil HDPE	Cradle-to-gate	No	UK wheat straw to high-density polyethylene	Walker, S., Ryan, A., Rothman, R., (2022). Tipping points in polymer life cycle greenhouse gas emissions, In press, Research Square, (Version 1), pages 1-15 [https://doi.org/10.21203/rs.3.rs-1715591/v1]
23	PBAT (Wheat straw, UK)	74%	4.20	2.41	Fossil LDPE	Cradle-to-gate	No	UK wheat straw to ethanol as feedstock.	Walker, S., Ryan, A., Rothman, R., (2022). Tipping points in polymer life cycle greenhouse gas emissions, In press, Research Square, (Version 1), pages 1-15 [https://doi.org/10.21203/rs.3.rs-1715591/v1]
24	PET via bio-MEG (Wheat straw, UK)	6%	2.78	2.62	Fossil PET	Cradle-to-gate	No	UK wheat straw, pre-treatment and fermented, dehydrated, and oxidised to MEG. Bio-based terephthalic acid from forest residues.	Walker, S., Ryan, A., Rothman, R., (2022). Tipping points in polymer life cycle greenhouse gas emissions, In press, Research Square, (Version 1), pages 1-15 [https://doi.org/10.21203/rs.3.rs-1715591/v1]
25	PET (High-density) (Sugar cane, BR)	-135%	-0.75	2.15	European	Cradle to gate	Yes	Brazilian Sugarcane ethanol	I. Tsiropoulos, A.P.C. Faaij, L. Lundquist, U. Schenker, J.F. Briois, M.K. Patel, Life cycle impact assessment of bio-based plastics from sugarcane ethanol, Journal of Cleaner Production, Volume 90, 2015, Pages 114-127, ISSN 0959-6526,
26	PET via MEG pathway (Sugar Cane, BR)	-28%	2.82	3.91	Naphtha	Cradle to gate	NA	Brazil sugar cane to ethanol to ethylene to MEG then shipped to UK for polymerisation to PET bottle	P. P. Van Uytvanck, B. Hallmark, G. Haire, P. J. Marshall, and J. S. Dennis. Impact of Biomass on Industry: Using Ethylene Derived from Bioethanol within the Polyester Value Chain. ACS Sustainable Chemistry & Engineering 2014 2 (5), 1098-1105
27	PET via MEG pathway (Willow, UK)	-4%	3.77	3.91	Naphtha	Cradle to gate	NA	UK willow to ethanol to ethylene to MEG then converted PET bottle	P. P. Van Uytvanck, B. Hallmark, G. Haire, P. J. Marshall, and J. S. Dennis. Impact of Biomass on Industry: Using Ethylene Derived from Bioethanol within the Polyester Value Chain. ACS Sustainable Chemistry & Engineering 2014 2 (5), 1098-1105

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
28	PEF via MEG pathway (Maize, USA)	-49%	2.05 *to* 2.38	4.4	PET from petrochemicals	Cradle to grave	Assumed no iLUC	US grown maize, wet milling to starch, then catalytically converted using hydrolysis and enzymes to dextrose and water, then enzymatic isomerization to dextrose and fructose	Eerhart, A.J.J.E, Faaija, A.P., and Patel, M.K. Replacing fossil based PET with bio-based PEF; process analysis, energy and GHG balance. Energy Environ. Sci., 2012
29	PET via MEG pathway (Wheat straw, Europe)	-1%	3.16	3.2	Petrochemical MEG	Cradle to grave	Yes	EU crop production to preparation, hydrolysis, fermentation and dehydration to bio-MEG production in India to esterification and polymerisation to PET in Europe	Gursel, I.V., Moretti, C., Hamelin, L., Jakobsen,L.G., Steingrimsdottir,M.M., Junginger,M., Høibye,L., Shen,L. (2021) Comparative cradle-to-grave life cycle assessment of bio-based and petrochemical PET bottles. Science of The Total Environment, Volume 793, ISSN 0048-9697.
30	PET via MEG pathway (Maize, wheat and sugar beet mix, EU)	23%	3.93	3.2	Petrochemical MEG	Cradle to grave	Yes	EU wheat straw to hydrolysis, fermentation and dehydration to bio-MEG production in India to esterification and polymerisation to PET in Europe	Gursel, I.V., Moretti, C., Hamelin, L., Jakobsen,L.G., Steingrimsdottir,M.M., Junginger,M., Høibye,L., Shen,L. (2021) Comparative cradle-to-grave life cycle assessment of bio-based and petrochemical PET bottles. Science of The Total Environment, Volume 793, ISSN 0048-9697.
31	Formic Acid (Microalgae)	-95%	0.10	2.01	Hydrolysis of methyl formate	Cradle to gate	No	Carbon capture and utilisation for CO2 via microalgae	Ahn, Y., Byun, J., Kim, D., Kim, B., Lee, C. & Han, J. (2019). System-level analysis and life cycle assessment of CO2 and fossil-based formic acid strategies. Green Chemistry. 21. 10.1039/C9GC01280J.
32	Fructose (Sugar beet, USA)		0.49			Cradle to gate	No	Sugar beet into liquid inverted sugars	Kis, F., Maravić, N., Kertész, S., & Šereš, Z. (2019). Life cycle assessment of liquid inverted sugar and high-fructose corn syrup. Analecta Technica Szegedinensia. 13. 28-39. 10.14232/analecta.2019.1.28-39.
33	Fructose (Maize, USA)		0.79			Cradle to gate	No	Corn grain into high fructose corn syrup	Kis, F., Maravić, N., Kertész, S., & Šereš, Z. (2019). Life cycle assessment of liquid inverted sugar and high-fructose corn syrup. Analecta Technica Szegedinensia. 13. 28-39. 10.14232/analecta.2019.1.28-39.
34	Furandicarboxylic acid* (Corn stover)		8 - 9	NA	*Terephthalic acid (PTA)	Cradle to gate	No	Maize corn stover is hydrolysed to sugar and then catalytically converted to 5-hydroxymethyl furfural; 5-hydroxymethyl furfural is converted to FDCA through catalytic oxidation	Chao Liang, Ulises R. Gracida-Alvarez, Troy R. Hawkins, and Jennifer B. Dunn ACS Sustainable Chemistry & Engineering 2023 11 (7), 2773-2783.
35	Furfural* (Furfuryl alcohol and tetrahydrofurfuryl alcohol) (Corn stover)		-1.90	NA		Cradle to gate	No	Maize corn stover (corncob) is hydrolysed to xylose and then dehydrated to obtain furfural	Chao Liang, Ulises R. Gracida-Alvarez, Troy R. Hawkins, and Jennifer B. Dunn ACS Sustainable Chemistry & Engineering 2023 11 (7), 2773-2783.

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
36	Furfural* (Furfuryl alcohol and tetrahydrofurfuryl alcohol) (Sugar beet pulp, USA)		0.27			Gate to gate	No	USA sugar beet pulp - Pyrolysis	Thompson,M., Mohajeri, A., Mirkouei, A. (2021) Comparison of pyrolysis and hydrolysis processes for furfural production from sugar beet pulp: A case study in southern Idaho, USA, Journal of Cleaner Production, Volume 311, 127695, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.127695.
37	Furfural* (Furfuryl alcohol and tetrahydrofurfuryl alcohol) (Sugar beet pulp, USA)		1.10			Gate to gate	No	USA sugar beet pulp - Hydrolysis	Thompson,M., Mohajeri, A., Mirkouei, A. (2021) Comparison of pyrolysis and hydrolysis processes for furfural production from sugar beet pulp: A case study in southern Idaho, USA, Journal of Cleaner Production, Volume 311, 127695, ISSN 0959-6526,
38	Glucaric Acid* (Sugar cane mill residues)		14.00			Cradle to gate	No	Sugarcane residues	Kapanji, K., Farzad, S., Görgens, J. (2021) Life cycle and sustainability assessments of biorefineries producing glucaric acid, sorbitol or levulinic acid annexed to a sugar mill, Journal of Cleaner Production, Volume 295, 126339, ISSN 0959-6526.
39	Glucaric Acid* (Maize stover)		1.68			Cradle to gate	No	Maize corn stover - heterogeneous catalytic glucose oxidation	Thaore,V.B., Armstrong, R.D., Hutchings, G.J., Knight, G.W., Chadwick, D., & Shah, N. (2020). Sustainable production of glucaric acid from corn stover via glucose oxidation: An assessment of homogeneous and heterogeneous catalytic oxidation production routes, Chemical Engineering Research and Design, Volume 153, Pages 337-349, ISSN 0263-8762.
40	Glucaric Acid* (Maize stover)		2.15			Cradle to gate	No	Maize corn stover - homogeneous catalytic glucose oxidation using nitric acid reagent	Thaore,V.B., Armstrong, R.D., Hutchings, G.J., Knight, G.W., Chadwick, D., & Shah, N. (2020). Sustainable production of glucaric acid from corn stover via glucose oxidation: An assessment of homogeneous and heterogeneous catalytic oxidation production routes, Chemical Engineering Research and Design, Volume 153, Pages 337-349, ISSN 0263-8762.
41	Glucose (Woody biomass residues)	-55%	0.80	1.76	Maize starch-based process	Cradle to gate	No	Enzymatic hydrolysis of woody biomass residues	Blanco, J.; Iglesias, J.; Morales, G.; Melero, J.A.; Moreno, J. (2020) Comparative Life Cycle Assessment of Glucose Production from Maize Starch and Woody Biomass Residues as a Feedstock. Applied Sciences, 10, 2946.

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
42	Lactic Acid (Maize Stover, USA)	-20%	7.20	8.98	Natural gas (Fei et al., 2020)	Cradle to gate	No	Corn stover derived L-lactic acid US	Chao Liang, Ulises R. Gracida-Alvarez, Troy R. Hawkins, and Jennifer B. Dunn ACS Sustainable Chemistry & Engineering 2023 11 (7), 2773-2783. Fei, Q., Liang, B., Tao, L., Tan, E., Gonzalez, R., Henard, C., Guarnieri, M. (2020). Biological valorization of natural gas for the production of lactic acid: Techno-economic analysis and life cycle assessment, Biochemical Engineering Journal, Volume 158, 2020, 107500, ISSN 1369-703X,
43	Levulinic Acid* (Sugar cane mill residues)		8.80			Cradle to gate		Sugarcane residues	Kapanji, K., Farzad, S., Görgens, J. (2021) Life cycle and sustainability assessments of biorefineries producing glucaric acid, sorbitol or levulinic acid annexed to a sugar mill, Journal of Cleaner Production, Volume 295, 126339, ISSN 0959-6526.
44	e-Methanol (Plasma, direct)	258.7	7.46	2.08	Natural gas *from Zang et al. 2021	Cradle to grave	No	PBGG - plasma assisted process, biogas feedstock	Delikonstantis, E., Igos, E., Theofanidis, S.A., Benetto, E., Marin, G.B., Van Geem, K. and Stefanidis, G.D., 2021. An assessment of electrified methanol production from an environmental perspective. Green Chemistry, 23(18), pp.7243-7258.
46	e-Methanol (Dry thermocatalytic)	35.7	2.82	2.08	Natural gas *from Zang et al. 2021	Cradle to grave	No	TBG - thermocatalytic process, biogas feedstock, energy from natural gas	Delikonstantis, E., Igos, E., Theofanidis, S.A., Benetto, E., Marin, G.B., Van Geem, K. and Stefanidis, G.D., 2021. An assessment of electrified methanol production from an environmental perspective. Green Chemistry, 23(18), pp.7243-7258.
47	e-Methanol (H2 from wind and solar and CO2, USA)	258.7	7.46	2.08	Methanol - Natural Gas	Cradle to gate Cradle to grave	No	CO_2 feedstock from industrial capture. Hydrogen from wind and solar	Zang, G., Sun, P., Elgowainy, A. and Wang, M., 2021. Technoeconomic and life cycle analysis of synthetic methanol production from hydrogen and industrial byproduct CO2. Environmental Science & Technology, 55(8), pp.5248-5257.
48	e-Methanol (CO2 hydrogenation, Canada)	-872	-1.39	0.18	Natural gas reforming	Cradle to gate	No	Captured CO_2 as feedstock. Hydrogen from wind and solar	Khojasteh-Salkuyeh, Y., Ashrafi, O., Mostafavi, E. and Navarri, P., 2021. CO2 utilization for methanol production; Part I: Process design and life cycle GHG assessment of different pathways. *Journal of CO2 Utilization*, *50*, p.101608.

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
49	Methanol (Biomass gasification)	-152.4	-0.54	1.03	Natural Gas	Cradle to gate	No	Biomass Gasification with electricity as co-product	Røyne, F., Ringström, E. and Berlin, J., 2015. Life cycle assessment of forest based raw materials for the Stenungsund chemical industry cluster.
50	Methanol (Pulp mill off gases)	-66.0	0.35	1.03	Natural Gas	Cradle to gate	No	KRAFT pulp mill stripper off gases	Røyne, F., Ringström, E. and Berlin, J., 2015. Life cycle assessment of forest based raw materials for the Stenungsund chemical industry cluster.
51	Naphtha (Vegetable oils)	-76%	0.79	3.313	Fossil derived	Cradle to gate		Vegetable oils derived	Feiferytė, A., Dvarionienė, J. and Gumbytė, M., 2015. Assessment of properties and life cycle of biosynthetic oil. *Journal of Cleaner Production*, *95*, pp.281-290.
52	Polylactic acid (Maize corn, UK processing)	-75%	0.94	3.74	Fossil Polystyrene	Cradle-to-gate	No	Global maize feedstocks.	Walker, S., Ryan, A., Rothman, R., (2022). Tipping points in polymer life cycle greenhouse gas emissions, In press, Research Square, (Version 1), pages 1-15 [https://doi.org/10.21203/rs.3.rs-1715591/v1]
53	Bio Propane (MSW)		gCO2e/MJ -500 to +80	gCO2e/MJ 76.0	LPG	Cradle to grave	No	Bio- or municipal solid waste	WLPGA (2023) Carbon Intensities, Renewable and Fossil Liquid Gases, LPG & DME
54	Propanediol (1,3-) (Algae feedstock)	64%	5.00	14.0	Fossil based	Cradle to grave	No	Fermentation of glycerol	Adom, F., Dunn, J.B., Han, J. and Sather, N., 2014. Life-cycle fossil energy consumption and greenhouse gas emissions of bioderived chemicals and their conventional counterparts. Environmental science & technology, 48(24), pp.14624-14631.
55	Propanediol (1,3-) (Algae feedstock)	37%	8.00	14.0	Fossil based	Cradle to grave	No	Glycerol fermentation to 3-HP the hydrogenation to Propanediol (1,3-)	Adom, F., Dunn, J.B., Han, J. and Sather, N., 2014. Life-cycle fossil energy consumption and greenhouse gas emissions of bioderived chemicals and their conventional counterparts. Environmental science & technology, 48(24), pp.14624-14631.
56	Propylene Glycol (Algae feedstock)	67%	2.70	8.1	Fossil based	Cradle to grave	No	Hydrogenation of glycerol	Adom, F., Dunn, J.B., Han, J. and Sather, N., 2014. Life-cycle fossil energy consumption and greenhouse gas emissions of bioderived chemicals and their conventional counterparts. Environmental science & technology, 48(24), pp.14624-14631.
57	Sorbitol (Sugar cane mill residues)		3.55			Gate to gate	No	Hydrogenation of glucose	Kapanji, K.K., Farzad, S. and Görgens, J.F., 2021. Life cycle and sustainability assessments of biorefineries producing glucaric acid, sorbitol or levulinic acid annexed to a sugar mill. Journal of Cleaner Production, 295, p.126339.

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emis. (kg eq. CO2/kg)	Fossil Comparator (kg eq. CO2/kg)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
58	Sorbitol (Sugar cane mill residues)		6.70			Cradle to gate		Enzymatic production of glucose from biomass/hydrogenation of glucose	Kapanji, K.K., Farzad, S. and Görgens, J.F., 2021. Life cycle and sustainability assessments of biorefineries producing glucaric acid, sorbitol or levulinic acid annexed to a sugar mill. *Journal of Cleaner Production*, *295*, p.126339.
59	Succinic Acid (1,4-) (Corn stover residues)	-30% -85% -24%	1.36	i) 1.94 ii) 8.82 iii) 1.78	i) fossil succinic acid ii) adipic acid iii) maleic anhydride	Cradle to gate	No	Corn stover & Succinic acid recovery via LLE (extraction of purified chemical from fermentation broth via liquid-liquid extraction method)	Cok B, Tsiropoulos I, Roes AL and Patel MK, Succinic acid production derived from carbohydrates: An energy and greenhouse gas assessment of a platform chemical toward a bio-based economy. *Biofuels Bioprod Biorefining* **8**: 16–29 (2014).
60	Succinic Acid (1,4-) (Corn stover residues)	-62% -92% -59%	1.85	i) 1.94 ii) 8.82 iii) 1.78	i) fossil succinic acid ii) adipic acid iii) maleic anhydride	Cradle to gate	No	Corn stover & succinic acid recovery via EDI (extraction of chemical from fermentation broth via electrodeionization)	Cok B, Tsiropoulos I, Roes AL and Patel MK, Succinic acid production derived from carbohydrates: An energy and greenhouse gas assessment of a platform chemical toward a bio-based economy. *Biofuels Bioprod Biorefining* **8**: 16–29 (2014).
61	Bio-Surfactant (Palm kernel oil (PKO)	77%	5.27	2.97	petrochemicals-derived fatty alcohol (FA) (petro-FA)	Cradle to gate	No	Alcohol ethoxylates surfactants produced via ethoxylation of fatty alcohol from PKO.	Shar et al., 2016
62	Bio-Surfactant (Sugarcane bagasse, BR)	681%	17.10	2.19	Petrochemical ethoxylated alcohol *Akizu-Gardoki, O., de Ulibarri, B., Iturrondobeitia, M., Minguez, R. and Lizundia, E., 2022.	Cradle to grave	No	Production of sophorolipid BSs from sugarcane bagasse using processes that are integrated within a lignocellulosicsugarcane-to-ethanol biorefinery.	Elias, A.M., Longati, A.A., Ellamla, H.R., Furlan, F.F., Ribeiro, M.P., Marcelino, P.R., dos Santos, J.C., da Silva, S.S. and Giordano, R.C., 2021. Techno-economic-environmental analysis of sophorolipid biosurfactant production from sugarcane bagasse. Industrial & Engineering Chemistry Research, 60(27), pp.9833-9850. *Akizu-Gardoki, O., de Ulibarri, B., Iturrondobeitia, M., Minguez, R. and Lizundia, E., 2022. Ecodesign coupled with Life Cycle Assessment to reduce the environmental impacts of an industrial enzymatic cleaner. *Sustainable Production and Consumption*, *29*, pp.718-729.
63	Bio-Surfactant (Sugarcane bagasse, BR) * Hot water pretreatment	336%	9.55	2.19	Petrochemical ethoxylated alcohol	Cradle to grave	No	Hot water bagasse pre-trestment and ultrafiltration for BS recovery.	Elias, A.M., Longati, A.A., Ellamla, H.R., Furlan, F.F., Ribeiro, M.P., Marcelino, P.R., dos Santos, J.C., da Silva, S.S. and Giordano, R.C., 2021. Techno-economic-environmental analysis of sophorolipid biosurfactant production from sugarcane bagasse. Industrial & Engineering Chemistry Research, 60(27), pp.9833-9850.

Appendix D: GHG emissions for bio-based chemicals and fossil comparators from industry data/studies

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emissions (kgCO2e / kg of bio-product)	Fossil Comparator GHG Emissions (kgCO2e / kg of product)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
	Acetaldehyde (Sugar cane, SEKAB, maize or sugar beet)	-113%	-0.75	5.7	NA - Assume fossil ethylene from naphtha	Cradle to gate	Not specified	Sugarcane, Maize or sugar beet	SEKAB (2014) Acetaldehyde SEKAB Biofuels & Chemicals. Available at: https://www.agrobiobase.com/en/database/bioproducts/consumers-goods/acetaldehyde
	PlantMEG (Sugar beet, Avantium, USA)	-32% -57% -83%)	0.57	1.41 1.32 3.32	MEG from Naptha, Saudi Arabia MEG from Shale-Gas, USA MEG from Coal, China	Cradle to grave	No	Sugar beet to sucrose to MEG	Avantium Renewables Chemistries (2022) Third Party and Critically Reviewed Ray plantMEG™ Life Cycle Assessment (LCA) Compliant with the guidelines of ISO 14040/14044
	PET (Sugar cane, Braksem, BR)	-217%	-2.15	1.83	NA	Cradle to gate	Yes	Braskem bio-based PE resin. Sugar cane, Brazil, fermentation to ethanol to ethylene to polyethylene. Includes embodied CO2 and fossil fuel substitution credits.	E4tech & LCAworks. Environmental assessment of Braskem's bio-based PE resin - Summary of the life cycle assessment, land-use change and water footprint reports. (2013)
	PEF via MEG pathway (Avantium)	-62%	100% PEF bottle	90% PET + 10% PEF bottle	Oil	Cradle to grave	No	Wheat starch catalytic conversion to fructose, FDCA polymerisation with Bio-MEG	Plum, M. et al. 2023: Case Studies Based on Peer-reviewed Life Cycle Assessments – Carbon Footprints of Different Renewable Carbon-based Chemicals and Materials
	FibreRight's VAMOS Lactic Acid (MSW)	22% -55%	1.99	i) 1.64 ii) 4.43	i) LA from sugarcane ii) Synthetic LA	Cradle-to-gate	No	Second generation sugars derived from municipal solid waste	FibreRight LCA Results
	Ingeo Biopolymer Drinking Cups (Maize)	-51%	2.52	5.2	PET for drinking cup	Cradle-to-grave	No	Maize to dextrose to lactic acid to lactide to polylactide.	PE Americas (2009) Comparative Life Cycle Assessment Ingeo™ biopolymer, PET, and PP Drinking Cups. Available at: https://www.natureworksllc.com/~/media/files/natureworks/what-is-ingeo/why-it-matters/lca/pea_cup_lid_lca_fullreport_reviewstatement_121209_pdf.pdf?la=en
	UPM BioMEG	-116%	-0.30	1.85	Fossil MEG Ecoinvent	Cradle-to-gate	No	Industrial wood and sawdust, fermentation to sugars and chemicals	Holger, J. (2023) UPM Biofore - Beyond Fossils
	Celtic Renewables* i) Acetone ii n-Butanol iii) Ethanol	i) 74% ii) 69% iii) 63%	kgCO2e/kg dry i) 1.77 ii) 1.76 iii) 0.52	kgCO2e/kg dry i) 4.59 ii) 4.58 iii) 3.03	Fossil	Cradle-to-gate	No	Whiskey distillery residues and waste potatoes	Celtic Renewables (13th October, 2021) Summary of ERM's Carbon Footprint Assessment

Ref	Bio-Chemical and/or Pathway	% Change in CO2e	Bio-based GHG Emissions (kgCO2e / kg of bio-product)	Fossil Comparator GHG Emissions (kgCO2e / kg of product)	Fossil Comparator	LCA System boundary	iLUC	Bio-based Pathway	Citation
	Lignocellulosic s biomass - Sawdust (Circa Group) Dihydrolevogl ucosenone (Cyrene)	87%	1.4	10.7	Fossil DMF	Cradle-to-gate	No	Waste cellulose (sawdust etc)	Circa, 2023. Private communications with S. Hickingbottom, General Manager, Circa Group, www.circa-group.com, 12 December 2023.