UK Top Bio-based Chemicals Opportunities

E4tech (UK) Ltd for LBNet

December 2017

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Executive summary

Bio-based chemicals could play a key part in a sustainable, low carbon chemicals sector in combination with recycling and the pursuit of other sustainability characteristics such as low toxicity. They offer the opportunity to generate low carbon energy at the end of the useful life cycle of a product or act as a carbon store. Developing bio-based chemicals in a sustainable manner presents challenges and substantial new business opportunities. The UK has a very strong science base with capabilities to take on these challenges, and an evolving ecosystem of large and small companies increasingly active in bio-based chemicals.

The global opportunities offered by the transition to a more sustainable, low carbon economy are vast, and the last decade has seen a substantial increase in interest in bio-based chemicals with many drop-in or novel bio-based chemicals being developed and introduced to the market. A 2004 US Department of Energy study on “Top Value Added Chemicals from Biomass” was seminal in attracting interest to the sector and steering academic and industrial activities, and LBNet has commissioned E4tech to investigate the attractiveness of bio-based chemicals and the opportunity they could present for the UK.

The UK’s chemical industry employs around 105,000 people and generates a gross added value of about £9bn per year. Building on this basis, the opportunity to generate additional jobs and value through bio-based chemicals could be very large. A review of UK activities has identified around 25 industry players (ranging from start-up companies to large corporates) and around 10 universities, which are actively developing bio-based chemical routes. These activities are complemented by a strong national science base, and a number of collaborations between industry and academia are already in place. However, additional research and infrastructure investments would accelerate development of the sector and establish the UK as a leading centre for bio-based chemical innovations. Taking a lead at this early stage of development of the sector will open global opportunities for UK industry and generate significant economic value in the UK.

An international literature review and interviews with many UK-based players led to the identification of around thirty interesting bio-based chemicals in terms of market and development potential (Table 1-1).

Table 1-1 List of Bio-based chemical opportunities in alphabetical order

1,3-Butanediol (1,3-BDO)	Fatty alcohols	Malic acid
1,3-Propanediol (1,3-PDO)	Fumaric acid	Methanol
2,5-Furandicarboxylic acid (FDCA)	Furfural	Methyl methacrylate (MMA)
3-Hydroxypropionic acid (3-HP)	Glucaric acid	Muconic acid
5-Hydroxymethylfurfural (HMF)	Glycerol	n-Butanol
Acrylic acid	Isoprene	Polyhydroxyalkanoates (PHA)
Adipic acid	Itaconic acid	Propylene glycol
Butadiene	Lactic acid	Paraxylene (p-Xylene)
D-Mannitol	Levoglucosenone	Succinic acid
Epichlorohydrin	Levulinic acid	Terpenoids
Ethanol	L-Lysine	Xylitol

An in-depth assessment of market attractiveness and UK strengths was carried out for each of the bio-based chemicals to identify the most promising development opportunities for the UK. Market attractiveness was determined based on distinctive functionality and sustainability features, potential market value, and existing competition. UK strength was determined based on UK activities and capabilities in relation to the bio-based chemical in question. The results of the assessment are presented in a matrix which shows the relative positioning of the bio-based chemicals in relation to the criteria considered (Figure 1-1).

Figure 1-1 Assessment of bio-based chemicals market attractiveness and UK strengths. Legend: 3-HP (3-Hydroxypropionic acid), HMF (5-Hydroxymethylfurfural), PHA (Polyhydroxyalkanoates), p-Xylene (Paraxylene), FDCA (2,5 Furandicarboxylic acid)

The analysis shows that there is a range of bio-based chemicals with high market attractiveness for which the current strength of UK positioning varies widely (top and bottom quadrants on the right). This grouping is the one considered of greatest interest and one in which existing areas of strength should be strengthened further and new strengths developed. There is also a grouping of bio-based chemicals where the UK shows good strengths but where market attractiveness may be medium to low. Investment into further strengthening the UK position should pay careful consideration to the potential market attractiveness.

The top bio-based chemicals opportunities that could be the focus of near term development in the UK and generate benefits to the UK economy are listed in Table 1-2.

Table 1-2 Top 20 bio-based chemical opportunities for the UK

Top 10		11 to 20	
1	**Lactic acid**	11	Xylitol
2	**2,5-Furandicarboxylic acid (FDCA)**	12	3-Hydroxypropionic acid (3-HP)
3	**Levoglucosenone**	13	D-Mannitol
4	**5-Hydroxymethylfurfural (HMF)**	14	Polyhydroxyalkanoates (PHA)
5	**Muconic acid**	15	Fatty alcohols
6	**Itaconic acid**	16	Fumaric acid
7	**1,3-Butanediol (1,3-BDO)**	17	Succinic acid
8	**Glucaric acid**	18	p-Xylene
9	**Levulinic acid**	19	Methanol
10	**n-Butanol**	20	Adipic acid

Lactic acid is used in the production of degradable polyesters, such as PLA, with large market potential as a result of growing environmental concerns and government regulations related to the use of petroleum derived, non-renewable plastics. The UK has a competitive position in lactic acid development, with UK based companies, such as Plaxica and Cellulac, having successfully generated value from lactic acid technology development, licensing and manufacturing.

2,5-Furandicarboxylic acid (FDCA) has a large market potential associated with the displacement of petroleum derived chemicals in various polymer applications, such as polyethylene terephthalate (PET), as a result of demand for sustainable plastics with enhanced functionality. FDCA derivatives have a number of interesting features which include degradable plastics and polymers, as well as improved functionality compared to their petroleum derived alternatives. The UK has good strengths in FDCA development, with several academic and commercial activities on FDCA, including the University of Liverpool, the University of York, the University of Manchester, and Biome Bioplastics. Besides developing pathways to produce FDCA from biomass, the activities also focus on production of novel polyester polymers with advanced functionalities.

Levoglucosenone is attractive as a high value ingredient in the pharmaceutical, flavour, fragrance and pheromone industry and for its conversion into commodity chemicals used for the production of solvents and polymers, which could provide safer and healthier alternatives to existing solvents. Few companies are developing levoglucosenone, and the UK is in a relatively good position with respect to commercialising the production of levoglucosenone and its derivatives through, for example, the activities of UK based company Circa Sustainable Chemicals UK.

Similarly to FDCA, **5 Hydroxymethyl furfural** (**HMF)** is attractive due to its versatility in producing new homo and co-polymers with advanced functionalities and improved degradability. These polymers could replace petroleum derived alternatives in elastomer, adhesive and coating applications, thus opening up a large market. Few companies are currently working on the development of HMF technology globally, and in the UK activities are focused on research, for example at Imperial College and at the University of Liverpool.

Muconic acid has a large market potential as it can be converted to a variety of chemicals and polymers. Currently there is no commercial production of muconic acid. The potential replacement of benzene and its derivatives in many polymer applications, such as polyethylene terephthalate (PET) and nylon fibres, makes muconic acid important in terms of sustainability. The development of new downstream applications and polymers from muconic acid is a key opportunity area. Well established synthetic biology and polymer science capabilities in UK universities and industry position the UK well for muconic acid technology development.

Itaconic acid could access large markets by replacing petroleum derived chemicals in many applications such as superabsorbent polymers (SAP) and unsaturated polyester resins (UPR). Although several large companies are engaged in the development of itaconic acid, the technology is still at an early stage, leaving space for other developers. The UK has strengths in relation to itaconic acid, with industrial and academic activities related to its development and that of its polymer derivatives, including activities at Itaconix, the University of York and the University of Nottingham.

1,3-Butanediol (1,3-BDO) could access large markets through its conversion to chemicals such as 1,3 butadiene. Industrial and academic activity in the UK is focused on clostridium fermentation technology, an area in which the UK is strong. Furthermore, the UK has the potential to create an integrated supply chain for production of 1,3-BDO for specialty product applications.

Glucaric acid has a potentially large opportunity as a replacement for phosphate builders in detergent applications, where environmental regulation is driving a move away from phosphates, creating an opportunity for this chemical to tap into the large personal and home care market. Johnson Matthey's work on scaling up of bio-based glucaric acid provides a competitive position for the UK in relation to this chemical.

Levulinic acid is attracting interest from chemical companies as a source of green solvents and for the production of polymers with advanced functionalities, which could replace petroleum derived plastics. Levulinic acid technology relies on the pretreatment and thermochemical conversion of biomass, but the UK lacks strength in scaling up and demonstrating these technologies.

The **n-Butanol** market is large and could potentially grow in the near term mainly due to increased consumption as a solvent in formulated products and as a feedstock for synthesis. Very few players currently work on the commercialisation of lignocellulosic butanol, and the UK is well positioned, with several industrial activities related to technology development, and scale up.

The UK is also well positioned for the development of chemicals such as **methylmethacrylate**, **acrylic acid**, **D-Mannitol**, **xylitol**, **3-hydroxypropionic acid** and **glycerol**, though their market attractiveness is lower. For example, in the case of acrylic acid or glycerol there is strong competition from other bio-based producers of these chemicals, and chemicals such as D-Mannitol or xylitol have relatively small markets and modest growth outlooks.

Overall, there is a range of promising bio-based chemicals with good market opportunities as a result of improved functionality and greater sustainability. The development of these bio-based chemicals and their derivatives is still at a stage where it is possible to innovate and compete, and the UK has promising strengths. The economic value of the markets that could be accessed by these bio-based chemicals is very large. There is therefore a strong rationale for investing in this area, though investments should follow more careful and detailed assessments of the technical and economic prospects of the specific bio-based chemical production pathways.

An important enabler for the development of bio-based chemicals will be technology advancements in feedstock pretreatment and the supply of the low cost renewable sugars. The UK has capabilities in this area, but requires investments in the testing and scaling up of the pretreatment technologies. Interviews indicated that UK businesses are often looking for these services outside the UK. So, there is a demand for open access testing and demonstration facilities able to provide affordable piloting and demonstration services to the UK's bio-based chemical sector.

Value is likely to arise from different parts of the value chain and business models. Given the relatively restricted biomass potential and high biomass costs in the UK, early stage production opportunities may most effectively target bio-based chemicals more suitable to medium volume production and possibly specialist applications with integration into downstream sectors e.g. 5 to 20 kilotons per year. Longer term larger scale production could be based on low cost wastes which are abundant in the UK[1]. In addition, significant value could be generated from technology licensing, as well as provision of R&D services and the export of engineering services.

An important opportunity exists in relation to the development of new applications for the derivatives of bio-based chemicals. The focus should be on development of innovative bio-based products which outperform traditional fossil-based products, as improved functionality and value will result in a strong end-users driver.

Bio-based chemicals could lead to environmental benefits in the UK, particularly in terms of reduced carbon emissions and in conjunction with the move to a more circular economy. These benefits will depend on the end-of-life of the products, but benefits could be substantial especially through cascading uses of bio-based products eventually through to energy recovery. These benefits will also depend on the feedstock used, and will be most beneficial where lignocellulosic and waste feedstocks are employed.

Currently, bio-based chemicals must compete with petroleum derived products on price rather than on sustainability, and without policy support which incentivises their use, bio-based chemicals are less likely to be taken up by the market. For example, the UK has no policy that incentivises the use of degradable materials or plastics in consumer applications, while in January 2017 France introduced a policy which mandates the use of home compostable materials for all single-use supermarket bags and food catering packaging, leading to an increase in demand for compostable resin.

Seizing the opportunities in the bio-based sector will best be achieved through a range of supporting activities including research programmes and funding, the facilitation of networks and collaborations, the establishment of open access piloting and demonstration facilities, support for early stage companies, as well as demand side measures.

[1] 2014 House of Lords Science and Technology Select Committee report, "Waste or resource? Stimulating a bioeconomy"

1 Introduction

Bio-based chemicals are obtained through biological, chemical or physical transformation of plant or animal based feedstocks, which include sugar, starch, oils and fats, and lignocellulose from forestry, agricultural crops and organic waste. They could play a key part in a sustainable, low carbon chemicals sector in combination with recycling and the pursuit of other sustainability characteristics such as low toxicity. They offer the opportunity to generate low carbon energy at the end of the useful life cycle of a product or act as a carbon store, as long as the feedstocks they are produced from are sustainably sourced.

Bio-based chemicals are currently manufactured in low volumes globally due to the dominance of petrochemicals as a result of the low cost of oil, the difficulty of competing with the cost-effectiveness of well-established and large scale integrated oil refineries, and the lack of specific incentives for bio-based chemicals[2]. The petrochemicals sector is currently worth around £50 billion in the UK alone and provides commodity and specialty chemicals that are used in the manufacture of most of the polymers, materials and non-food chemical ingredients used in manufacturing. Many of these chemicals and intermediates can be produced from biological feedstocks in a low carbon sustainable way.

The desire to reduce greenhouse emissions and reliance on fossil fuels, develop regional bio-based industries, improve the sustainability of products (e.g. degradability) and in some cases their functionality, is driving an interest in bio-based chemicals. The last decade has seen a substantial increase in activity in bio-based chemicals with several drop-in or novel bio-based chemicals being developed and introduced to the market. A 2004 US Department of Energy study on "Top Value Added Chemicals from Biomass"[3] was seminal in attracting interest in the sector and steering academic and industrial activities.

A report commissioned by LBNet[4] showed that the UK has a growing academic and industry base in bio-based fuels and chemicals, alongside a strong and established chemicals industry. This makes the UK potentially well positioned to take advantage and benefit from growth opportunities in the bio-based chemicals area. Although the UK government recognises the importance of the bioeconomy to the UK economy and is developing a high level Bioeconomy Strategy, there is currently no UK-wide strategic approach to developing the bio-based chemicals sector.

In this report we will examine the extent to which bio-based chemicals represent an opportunity for the UK. The aim of this study is to identify and assess potential bio-based development opportunities by:

- reviewing the status and strengths of the UK's bio-based sector, taking into consideration academic and industrial activities
- developing and applying a framework for determining promising bio-based development opportunities for the UK.

[2] Capital Economics and E4tech (2016), Evidencing the Bioeconomy
[3] NREL, PNNL (2004), Top Value Added Chemicals from Biomass
[4] E4tech (2016), An initial feasibility study of the potential for the establishment of lignocellulosic biorefineries in the UK

2 UK activities and capabilities in bio-based chemicals

An inventory of UK activities relevant to bio-based chemicals has been created to provide an indication of the level and strength of current activities and capabilities. Emphasis has been put on industrial and academic activities related to the development of specific bio-based pathways, as it provides evidence on how these could serve as a platform from which to develop the industry.

Public domain information was reviewed for R&D, technology development, scale up and manufacturing activities related to the development and production of bio-based chemicals in the UK. This was backed up by interviews conducted with representatives of the UK's chemical industry and academics active in the development of bio-based chemicals and related technologies.

The aim of the interviews was to understand the nature of organisations' activities and their interests in the bio-based sector, particularly focusing on specific bio-based chemicals or production pathways under development. The interviewees were asked to describe their organisation's activities and capabilities relating to technology development, facilities and production, and partnerships with other industrial or technology development organisations.

The information obtained from the interviews provided insight into the status of the UK's bio-based industry and the activities around specific bio-based chemicals and bio-based products.

UK industrial players

Table 2-1 provides an overview of UK-based companies active in the production and development of bio-based chemicals. The list provides a snapshot of the current UK bio-based industry and its activities, but should not be considered to be exhaustive and will certainly change with time.

The results obtained from the literature search and interviews (Table 2-1) suggest that most of the UK's industry activities are in the early stages of bio-based chemicals development, typically between technology readiness level 3 and 5 (TRL 3 – 5)[5]. Early stage technology development and product innovation are still the primary focus of the UK industry. There are currently few companies producing bio-based chemicals at commercial, or close to commercial, scales in the UK. Companies such as Green Biologics, Butamax or Croda, who have well established R&D centres in the UK are demonstrating production in the USA or Brazil for a variety of reasons including costs, support programmes and infrastructure.

Good partnerships and interactions between SMEs and universities are developing in the UK's bio-based sector. Companies such as Green Biologics, Lucite International and Chain Biotechnology are working with universities such as Nottingham and York, and the Centre for Process Innovation at Wilton on the production of bio-based chemicals such as butanol. Similarly, Biome Bioplastics is collaborating with several UK universities (see Table 2-1) on the development of new functional polyesters derived from lignocellulose. These interactions generate new knowledge and innovation leading to better processes, new products and services, which are crucial to maintain and improve the UK's competitiveness.

Several major UK chemical and petrochemical industries (e.g. BP, Invista, Croda, Ineos, Lucite International) are active in the development of bio-based chemical routes. Companies such as Croda

[5] TRL definitions: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

and Lucite International have their own research and pilot facilities with capabilities to develop and scale-up technologies. Catalysis expertise is available in companies like Johnson Matthey, a leading company for development of catalytic technologies and catalysts for the chemical and pharmaceutical industry. In addition, the UK has the skills and expertise to construct and operate bio-based chemicals manufacturing plants. These skills and capabilities provide a good foundation on which to build the UK's bio-based sector.

The activities described above largely encompass the transformation of sugars into bio-based chemicals through fermentation or catalytic chemical routes (or hybrids of the two). The importance of biomass waste and residues as a source of sustainable sugars implies that the UK will require technology for the conversion of crop residues (e.g. cereal straw, forest residues) and wastes (e.g. paper and the biological fraction of municipal solid waste) into sugars and other platform chemicals. The UK has a strong research base in this area at the Universities of York, Nottingham and Aberystwyth, with pilot scale facilities for biomass processing at the Biorenewables Development Centre (BDC) in York, the Beacon Biorefinery at Aberystwyth and Centre for Process Innovation (CPI) in Wilton. In addition the Department for Transport has recently funded demonstration scale activities for biomass-based fuel production by Celtic Renewables Ltd (using spent distillers grain) and Nova Pangaea (using birchwood), and a small demonstration facility for the conversion of the biological fraction of municipal solid waste to butanol is being developed with European funding from Bioenergy Sustaining the Future (BESTF) by Wilson Bio-chemical Ltd, in association with the Biorenewables Development Centre and Universities of York and Nottingham. Despite the considerable activity in this area, access to large scale quantities of sugars derived from non-food biomass represents a barrier to sustainable bio-based chemicals development in the UK. Establishing a demonstration plant capable of supplying bio-based chemicals companies with the appropriate feedstock (biomass derived sugars are more heterogeneous than those from first generation sources such as sugar beet or cane) at appropriate scale (tons) would help establish a firm basis for a sustainable bio-based chemicals sector in the UK and attract companies from outside the UK.

Table 2-1 Inventory of UK bio-based industry activity

Company	Activity Type, UK related	Products, UK related	Bio-based product interests	Technology status	Active partnerships in the UK
Akzo Nobel	Manufacturing and R&D – several manufacturing sites across the UK	Mainly coatings – aerospace, packaging, decorative, etc.	Bio-based polymers	Different stages from early research to commercial production	Bio-based related partnership in the UK unknown
BASF	Manufacturing and R&D - with 9 manufacturing sites across the UK	Polyurethane systems, industrial chemicals, omega-3 fatty acids , bio-pesticides, etc.	n-butanol, FDCA, PG, succinic acid	Different stages from early research to commercial production	University of Huddersfield
Biome Bioplastics	R&D and technology development - UK Based	Polyester polymer with advanced functions	FDCA	Development stage	Imperial College London, Aston University, University of York, University of Manchester, University of Liverpool
Butamax (JV BP DuPont)	R&D, technology development and scale up - demonstration and piloting facilities in Hull	Fuel	Iso-butanol	Demonstration activities in the UK, commercial production of iso-butanol in the USA	BP and DuPont joint venture
Calysta	R&D - development of metabolic pathways and manufacturing - UK based (Teesside)	Feed ingredients for fish, livestock and pets	Single cell protein	Advanced	Bio-based related partnership in the UK unknown
Cellucomp	R&D and technology development - UK Based	Rheology modifiers for paints and coatings	Composite material, cellulosic fibres	Advanced	CPI UK
Cellulac	R&D and technology development - UK Based	Biodegradable polymers	Sodium lactate, ethyl lactate & D(-)lactic acid	Advanced	Bio-based related partnership in the UK unknown
Celtic Renewables	R&D, technology development and manufacturing – UK	Fuel	n-butanol	Advanced	Bio-based related partnership in the UK unknown
CHAIN Biotech	R&D - metabolic pathway engineering - UK	Pheromones, fragrances, insecticides and antibiotics	1,3-Butanediol (n-butanol & acetone)	Development stage	Green Biologics, University of Nottingham, Imperial College London, Green Biologics, Lucite Int. UK, Ingenza

Company	Activity Type, UK related	Products, UK related	Bio-based product interests	Technology status	Active partnerships in the UK
Circa Sustainable Chemicals UK	R&D and technology development - UK	Aprotic solvents	Levoglucosenone	Advanced	University of York, University of Huddersfield
Croda	Manufacturing , technology development and scale up - several manufacturing sites in the UK	Specialty chemicals, agrochemicals, lubricants, surfactant	Ethylene oxide (from bioethanol)	Commercial - in USA	Bio-based related partnership in the UK unknown
DuPont	Manufacturing - several manufacturing sites in the UK	Resins, fibres and coatings	1,3-PDO, isoprene, iso-butanol and other chemicals.	DuPont is developing a number of bio-based chemicals which are currently at different development stages: from early research to commercial production	JV with BP on iso-butanol
Ensus	Manufacturing - operates one of the largest bioethanol plants in Europe, NE England	Biofuels	Ethanol	Commercial - in the UK	Bio-based related partnership in the UK unknown
Futamura	R&D and manufacturing in the UK	Packaging film from cellulose	Composite polymer- cellulose	Commercial - in the UK	Bio-based related partnership in the UK unknown
Green Biologics	R&D in the UK and manufacturing in the USA	Fuel, bulk chemicals	Butanol and acetone	Commercial - in the USA	University of Nottingham, Lucite International UK, Ingenza Ltd, UK-CPI, Chain Biotechnology Ltd
GSK	R&D and manufacturing in the UK	Pharmaceuticals	Interested in solvents - n-butanol, (not to produce but use in their processes)	Not known	CoEBIO3 and University of Manchester - although not related to bio-based chemicals
INEOS	R&D and manufacturing in the UK (oil refineries)	Chemicals, Olefins Polymers	Cellulosic ethanol - US activities only	Advanced - USA only	Bio-based related partnership in the UK unknown

Company	Activity Type, UK related	Products, UK related	Bio-based product interests	Technology status	Active partnerships in the UK
Itaconix	R&D and manufacturing - UK based	Specialty polymers, home care and industrial products	Itaconic acid	Commercial	Bio-based related partnership in the UK unknown
Johnson Matthey	R&D, technology development, scale up and manufacturing - in the UK	Catalyst products and technology licensing	Butanediol, biodiesel - technology development with Myriant - USA	Different stages from early research to commercial	Bio-based related partnership in the UK unknown
Lucite International	R&D, technology development, scale up and manufacturing - 3 production sites in the UK	Methacrylate monomers and polymers	Methyl methacrylate	Development stage	Green Biologics, University of Nottingham, Imperial College London, Green Biologics, Ingenza, Chain Biotechnology Ltd.
Nova Pangaea	R&D, technology development	Converting wood waste into sugars and other products for bio-based chemicals and fuels	Cellulosic sugars as a platform for bio-based chemicals	Demonstration scale	University of Bath
Oxford Biotrans	R&D - UK Based	Enzyme production	High value chemicals - Flavours	Development stage	University of Oxford
Plaxica	R&D and technology development - UK Based	Technology licensing for PLA polymer and lactic acid	D lactic acid, lactic acid, PLA	Commercial	Imperial College London
Rebio	R&D - UK based (modified strains of microorganisms)	Biodegradable polymers	D- Lactic acid	Development	CPI UK, University of Bath
Syngenta	R&D and manufacturing	Agro chemicals, biocontrol	Surfactants and low phytotoxicity solvents e.g. n-butanol	No activities related to bio-based chemicals	Bio-based related partnership in the UK unknown
Wilson Bio-Chemical	R&D and Technology Development	Converting the biological fraction of municipal solid waste into bio-based chemicals	n-butanol, citric acid	Development	Biorenewables Development Centre, University of York, University of Nottingham

UK R&D and technology development services

There are several organisations in the UK that provide technology, R&D, scale up and demonstration services relevant to the production of bio-based chemicals. Access to these enabling skills and expertise is vital to companies that are developing and commercialising new bio-based technologies. This is particularly true for SMEs which often do not have sufficient in-house skills or capabilities for development, demonstration and scale-up.

Synthetic biology and biocatalytic R&D capabilities are well established in the UK and currently available within a number of research centres. A spin-out company from the University of Edinburgh, Ingenza, is an example of a commercial research centre which provides a wide range of services in protein engineering, fermentation and synthetic biology. The company has built its skills and capabilities by servicing UK and international customers in the pharmaceutical, food and chemical industries.

The Centre for Process Innovation (CPI) is an open access technology innovation centre in the UK that provides access to large scale fermentation processes. Open access facilities for biomass pretreatment or gasification technology at the relevant scale are currently not readily available in the UK, and this may represent a gap in the UK's capabilities to commercialise bio-based chemicals which rely on these technologies.

Table 2-2 provides an overview of organisations that provide R&D and technology development services in the UK.

Table 2-2 R&D and technology development service organisations in the UK

Company /organisation	Activity	Expertise and Capabilities
Biocatalyst Ltd.	R&D and manufacturing	Enzyme development, enzyme production
Biorenewables Development Centre (BDC)	Innovation Centre	Process and product development, Scale-up
Centre for Process Innovation (CPI)	Technology innovation centre	Process and product development, prototyping, scale up and demonstration, modelling and simulation, engineering, etc.
CoEBio3	Innovation, R&D and technology development	Biocatalysis and biocatalytic manufacture for chemicals and pharmaceuticals
IBioIC	Innovation Centre	Connects industry, academia and government and facilitates collaborations, provides scale-up capabilities, creates networks and develops skills
Ingenza	R&D and technology development - UK based centre	Synthetic biology, protein engineering, product development and fermentation technology
Scottish Association for Marine Science	R&D and science centre	Marine biotechnology, farming the sea

UK academic activities

UK universities are active in the bio-based chemicals space, as illustrated by Table 2-3. A diverse portfolio of bio-based chemicals is being researched, often in collaboration with industry and SMEs, as illustrated in Table 2-1. These activities provide a solid base for the development of the bio-based chemicals discussed in section 4.

The UK has a strong academic base in sciences which are relevant to the development of bio-based chemicals. These are:

- Synthetic Biology
- Biocatalysts and enzyme technology
- Chemistry
- Catalysis
- Chemical engineering
- Polymer Science
- Biomass processing

Synthetic biotechnology plays a key role in the development of microorganisms and enzymes which are capable of transforming materials and producing bio-based chemicals. There are several Synthetic Biotechnology Research Centres (SBRC) in the UK which focus on a wide range of applications. For instance, the SBRC at the University of Manchester focuses on the synthetic biology of fine and speciality chemicals, the University of Nottingham is developing synthetic biology organisms which convert single-carbon gases into valuable chemicals, the SBRC at Imperial College London is focusing, among other things, on biofuel applications. Other SBRCs are located at the Universities of Edinburgh, Warwick and Cambridge.[6]

Biomass processing using chemical or enzyme catalysis is an active area of research in UK universities including Aston, Bath, Cranfield, Newcastle, Nottingham, Teesside and York.

Strong bases in other relevant sciences such as chemistry, catalysis and polymer science are present across different UK universities such as York, Bath and Nottingham, University College London and Queen's University Belfast.

[6] Clarke L.J. and Kitney R.I. (2016), Synthetic biology in the UK - An outline of plans and progress

Table 2-3 Inventory of UK academic activity related to bio-based chemicals

University	Department	Molecules and Products	Technology
Imperial College London	Chemistry department	Carbohydrates	Ionic liquid extraction technology, deconstruction and fractionation of lignocellulosic biomass
Imperial College London	Chemistry department	Hydroxymethylfurfural (HMF)	Catalytic conversion of fructose, glucose and cellulose to 5-hydroxymethylfurfural (HMF)
University of Aston	European Bioenergy Research Institute	Levulinic acid, ethyl levulinarte	Fermentation of sugars
University of Bath	Centre for Sustainable Chemical Technologies (CSCT) at the University of Bath	Cyclic carbonates	Not known
University of Bath	Centre for Extremophile Research	Ethanol, biodiesel	Biocatalysis - enzyme engineering
University of Bath	Chemistry department	2-phenylethanol, arabinitol and lipids	Biorefining – details not known
University of Bath	Chemistry department	2-phenylethanol, arabinitol and lipids	Biorefining – details not known
University of Liverpool	Chemistry department	Hydroxymethylfurfural (HMF) and bio-based polyesters	Chemical conversion
University of Manchester	Satake Centre for Grain Process Engineering	Succinic acid	Fermentation
University of Newcastle	Chemical Engineering department	Polymers, including polyalkanes, polyethers, polyesters, polycarbonates and polyurethanes.	Chemical conversion
University of Nottingham	Chemical and Environmental Engineering department	Butadiene, 3-hydroxyproprionic acid, ethylene, propylene, isobutene, butadiene and isoprene.	Clostridium fermentation of C1 gases
University of Nottingham	Chemical and Environmental Engineering department	3-Hydroxypropaanoic acid (3-HP), acrylic acid, malonic acid, 1,3-Propanediol	Gene editing - Clostridium fermentation technology
University of Nottingham	Chemical and Environmental Engineering department	Terpene based Acrylate and Methaacrylate Polymers	Conversion of waste streams including food, forestry and agriculture

University	Department	Molecules and Products	Technology
University of Nottingham	Chemical and Environmental Engineering department	Butanol, commodity chemicals, citramalic acid (several products targeted in different research programmes)	Biocatalysts, and metabolic engineering - Clostridium fermentation
University of Reading	Chemistry department	Butadiene - including biopolymers, bioplastics, biocomposites, oleochemicals, and speciality and platform chemicals	Chemical and biological conversion of waste food and side products - farming residue and spent cereal grains, fish and meat waste
University of Teesside	Petroleum Engineering department	Long chain fatty acids, sugar/lipid and protein/lipid molecules. Exopolysaccharides. biosurfactants	Bacterial / algal fermentation
University of Warwick	Chemistry department	Polyurethanes, epoxy resins, polyesters, polyamides, polytriazoles, polyoxazoles and phenolic polymer composites	Conversion of plant oils
University of Warwick	Warwick Centre for Biotechnology and Biorefining	Organic chemicals	Pretreatment - biocatalytic breakdown of lignin
University of York	Chemistry department	Itaconic acid, 2,7-octanedione, furfural, platform chemicals, building blocks	Fermentation, chemical conversion
University of York	Green Chemistry Centre of Excellence	Polyesters, polyurethanes and polycarbonate	Polymerisation of bio-based itaconic anhydride and furfural into polyesters
University of York	Centre for Novel Agricultural Products	Citric acid, itaconic acid, glucaric acid, acrylic acid, bioethanol	Fermentation
University of York	Biology department	n-butanol and ethanol	Fermentation

Furthermore, there are 13 BBSRC Networks in Industrial Biotechnology and Bioenergy (NIBBs) which foster collaboration between academia, industry and policy makers, and seek opportunities to translate research and accelerate innovation in the UK's industrial biotechnology sector. The networks provide proof of concept funding and business interaction vouchers for collaboration initiatives between UK businesses and universities. This type of support action provides opportunities, especially for UK SMEs, to access state of the art research. These initiatives contribute to creation of new knowledge, capacity building and further strengthening of the UK's bio-based chemicals sector.

The 13 BBSRC NIBBs are[7]:

ADNet: Anaerobic Digestion Network

Biocatnet: Network in Biocatalyst Discovery, Development and Scale-Up

BioProNET: Bioprocessing Network

C1NET: Chemicals from C1 Gas

CBMNet: Crossing biological membranes

FoodWasteNet: Food Processing Waste and By-Products Utilisation Network

HVCfP: High Value Chemicals from Plants Network

IBCarb: Glycoscience Tools for Biotechnology and Bioenergy

LBNet: Lignocellulosic Biorefinery Network

Metals in Biology: The elements of Biotechnology and Bioenergy

NPRONET: Natural Products Discovery and Bioengineering Network

P2P: A Network of Integrated Technologies: Plants to Products

PHYCONET: Unlocking the IB potential of microalgae

[7] http://www.bbsrc.ac.uk/research/programmes-networks/research-networks/nibb/

3 Review of bio-based chemicals opportunities

In this section, we provide a list of chemicals that could represent a development and growth opportunity for the UK's bio-based chemicals sector.

A literature review has been conducted to identify bio-based chemicals which are recognised as having high potential globally. Studies conducted by the US Department of Energy and International Energy Agency have been reviewed, as well as previous UK studies on bio-based chemicals[8]. Publications and blogs[9] which specialize in bio-based chemicals have been searched for information on the most recent technology developments, global market trends and drivers of the bio-based industry.

In addition to the literature review, a workshop and interviews have been conducted to identify bio-based chemicals deemed of interest by the UK's chemical industry and academia. More than twenty companies and academic institutions provided input through the workshop and interviews.

Bio-based chemicals which have already reached commercial scale production and where strong partnerships between technology developers and manufacturers are present have not been selected for further consideration. This is mainly because for these bio-based chemicals the opportunity for the UK to create additional value is limited. An example is bio-based 1,4-Butanediol (1,4-BDO) produced by biological conversion of commodity sugars via *Escherichia coli*. This technology has been commercialised by Genomatica in 2013 and since then several commercial partnerships with large multinational manufacturers have been established (BASF, Cargill, Tate & Lyle and DuPont). However, opportunities related to production of bio-based 1,4-BDO via catalytic upgrading of bio-derived succinic acid are not excluded by this study as bio-based succinic acid is included in the list of bio-based chemicals to be assessed.

The bio-based chemicals identified are provided in alphabetical order in Table 3-1.

[8] "*From the Sugar Platform to biofuels and biochemicals*" E4tech, RE-CORS, Wageningen University. Final report for the European Commission. 2015.
Directorate-General Energy

[9] Biofuel Digest and Green Chemicals Blog

Table 3-1 List of bio-based chemicals opportunities in alphabetical order

1,3-Butanediol (1,3 BDO)	Fatty alcohols	Malic acid
1,3-Propanediol (1,3 PDO)	Fumaric acid	Methanol
2,5-Furandicarboxylic acid (FDCA)	Furfural	MMA (Methylmethacrylate)
3-Hydroxypropionic acid (3-HP)	Glucaric acid	Muconic acid
5-Hydoxymethylfurfural (HMF)	Glycerol	n-Butanol
Acrylic acid	Isoprene	Polyhydroxyalkanoates (PHA)
Adipic acid	Itaconic acid	Propylene glycol
Butadiene	Lactic acid	Paraxylene (p-Xylene)
D-Mannitol	Levoglucosenone	Succinic acid
Epichlorohydrin	Levulinic acid	Terpenoids
Ethanol	L-Lysine	Xylitol

The list of chemicals is not exhaustive, but captures the current focus of interest on bio-based chemicals globally and in the UK.

A short summary of key features and value propositions of the bio-based chemicals that will be further assessed in relation to their market attractiveness and UK positioning is provided below.

1,3-Butanediol (1,3-BDO) is a building block for high value products such as: pheromones, fragrances, insecticides and antibiotics. Conversion to products like 1,3 butadiene for synthetic rubber and specialist polymer resins could lead to large market opportunities in the millions of tonnes per year, with growth expected to be at least 2% per year in the near term.[10] UK based CHAIN Biotechnology Ltd has patented a technology for Clostridial fermentation of C5 and C6 sugars to 1,3 Butanediol, and suggests that production economics support relatively small standalone plants of up to a few kilotonnes per year, which could potentially be built in the UK.[11]

1,3-Propanediol (1,3-PDO) is mainly used (80%) to make the new polyester polytrimethylene terephthalate (PTT) which is mostly used in the carpet fibre industry. The diol structure of 1,3-PDO makes it particularly useful for producing polyester materials and other useful chemical building blocks. Personal care applications include functional uses as a humectant, preservative booster, solvent, carrier, and viscosity modifier. The 1,3-PDO market is relatively small, with demand in 2014

[10] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016

[11] CHAIN Biotechnology Ltd (2017), personal communication

at about 125 kilotonnes per year, but growing rapidly at 4%–7% per year in the fibre category.[12] The majority of PDO today is made using a bio-based process, as the economics appear to be favourable compared to a fossil route. Sugar fermentation and glycerol fermentation are two major routes for production of bio-based 1,3-PDO, with potential for improvement in yields when using crude glycerine or C5 sugars. The University of Nottingham is researching 1,3-Propanediol.

2,5-Furandicarboxylic acid (FDCA) can be used in a variety of industrial plastics, including bottles, textiles, food packaging, carpets, electronic materials and automotive applications. Perhaps one of the most interesting features of FDCA is its potential to provide an alternative to polyethylene terephthalate (PET) which is today widely used for production of plastic bottles and food packaging materials. Polyethylenefuranoate (PEF) derived from FDCA is claimed to provide better barrier, thermal, and mechanical properties compared to existing PET based packaging materials. In the UK there are several academic and commercial activities related to FDCA involving Biome Bioplastics, the Universities of Liverpool, Aston, York and Manchester, and Imperial College. Besides developing pathways to produce FDCA from biomass, the activities are also focused on production of novel polyester polymers with advance functionalities.

3-Hydroxypropionic acid (3-HP) is a platform chemical which can be converted into various industrial or end use chemicals e.g. 1,3-Propanediol, acrylic acid, methyl acrylate, acrylamide, etc. It can also be polymerised into degradable polyester polymers e.g. poly (3-Hydroxypropionic acid). The market for this chemical is still not well established, however the potential market could be large considering the market sizes of its derivatives. 3HP can be produced by aerobic fermentation of glucose. Other pathways include aerobic fermentation of glycerol by the *E. coli* strain and a two-step conversion process which involves glycerol fermentation by *Klebsiella pneumonia* into 1,3-Propanediol and conversion of 1,3-PDO into 3PA [13,14]. Cargill has acquired OPX who were developing a fermentation to 3-HP to bio-based acrylic acid process. Novozymes and Cargill collaborate on 3-HP as well, although BASF exited this partnership in 2015. The University of Nottingham is researching 3-Hydroxypropionic acid.

5-Hydroxymethylfurfural (HMF) is currently produced by a fructose dehydration process. HMF technology is not fully commercial, and production is about 100 kilotonnes globally. Thanks to its versatility, HMF was identified by the US Department of Energy as one of the most valuable platform chemicals.[15] HMF can be used to manufacture polyesters, polyamides and polyurethanes, as well as FDCA, which is used as a monomer for production of biodegradable plastic. HMF is also an intermediate in the production of levulinic acid (and formic acid). Another interesting feature of HMF is its potential to replace the carcinogenic formaldehyde in phenol-formaldehyde resins widely used in adhesive systems.[16] Currently there is not much activity in the UK on HMF.

Acrylic acid is widely used as monomer or co-monomer for manufacturing of various plastics, coatings, adhesives and elastomers. Polyacrylic acid or copolymers find applications in

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[12] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016

[13] *"Development of a two-step process for production of 3-hydroxypropionic acid from glycerol using Klebsiella pneumoniae and Gluconobacter oxydans*." Zhao L. Bioprocess Biosyst Eng. 2015 Dec;38(12):2487-95.

[14] "*Enhancement of 3-hydroxypropionic acid production from glycerol by using a metabolic toggle switch*" Keigo Tsuruno. Microb Cell Fact. 2015; 14: 155.

[15] https://greenchemicalsblog.com/2014/05/01/qa-ava-biochem-on-5-hmf/

[16] http://www.biofuelsdigest.com/bdigest/2017/02/05/avalons-bid-to-replace-carcinogenic-formaldehyde/

superabsorbent polymers, detergents, dispersants, flocculants and thickeners. Superabsorbent polymers (SAPs) are used primarily in disposable nappies. The market for acrylic acid is large at about 5 million metric tonnes per year, with projected growth rate of 4%–5% per year. Conventionally acrylic acid is produced from propylene feedstock. With the availability of cheap shale gas utilized to produce ethylene, the market has seen a reduction in propylene production and is projecting higher costs for acrylic acid, opening opportunities for biomass-derived products.[17] In the UK there are several large consumers of acrylic acid or its derivatives e.g. Akzo Nobel for acrylic coatings, Proctor & Gamble for Super Absorbent Polymer (SAP) applications. Companies such as Arkema, Cargill, Celanese, Genomatica, Myriant, Nippon Shokubai, Novozymes, OPX Bio, and SGA Polymers are currently developing technologies to produce acrylic acid from biomass e.g. sugars, glycerine.

Adipic acid is primarily used to produce nylon-6,6 for fibres and engineering resins. Petroleum-derived adipic acid is produced in a two-stage process that involves the oxidation of cyclohexane followed by nitric acid oxidation of the intermediate to adipic acid. The later steps of the process have a large impact on the sustainability of the overall process.[48] Bio-based adipic acid can be produced through several pathways, including biological conversion of plant based oils and fatty acids to adipic acid and aerobic oxidation of glucose followed by catalytic hydrogenation to adipic acid. Several companies are developing biobased adipic acid technology: DSM, Rennovia, Celexion, Genomatica, Deinove, Myriant and Amyris. The adipic acid market is estimated to be about 2.5 million tonnes per year, with projected growth rate of 3-5% per year.[18] In the UK there are no known bio-based activities related to this chemical.

Butadiene or 1,3 Butadiene. Butadiene is mostly used to produce styrene-butadiene rubber (SBR) to make tyres. Global production of butadiene is estimated at 10 million tonnes per year with expected growth of 1-2%.[19] It is currently produced from petroleum as a by-product of ethylene manufacturing. Bio-based routes for production of butadiene include direct C6 sugar fermentation or catalytic conversion of succinic acid obtained from sugar or syngas fermentation. Large international chemical companies including Braskem, Invista, Synthos, and Versalis are developing bio-based 1,3 butadiene. There are several activities related to the development of bio-based butadiene in the UK, including a collaboration between Invista, Lanzatech and the UK's CPI on C1 gas (single carbon gases e.g. CO, CO2, CH4) fermentation to butadiene.

D-Mannitol's major applications include food additives, pharmaceuticals and surfactants. Mannitol is a naturally occurring sugar alcohol which exhibits reduced caloric value compared to most of the sugars. It is not well metabolised in the body and it does not interact with insulin, so it is suitable for diabetics and adequate as a low caloric food ingredient. At present, D-mannitol is produced commercially by catalytic hydrogenation of fructose-containing syrups. The process has several disadvantages, it requires ultra-pure (expensive) raw materials (fructose and hydrogen) and it has a relatively low selectivity toward mannitol only about 50%.[20] Microbial conversion of fructose to D-

[17] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016
[18] https://www.ihs.com/products/adipic-acid-chemical-economics-handbook.html
[19] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016
[20] "*Process development for mannitol production by lactic acid bacteria*" by Niklas von Weymarn, Helsinki University of Technology Department of Chemical Technology Laboratory of Bioprocess Engineering 2002

mannitol does not require high purity hydrogen, however the microbes co-metabolise a significant amount of glucose for this process. D-mannitol's market is relatively small today <£250 million, but increasing demand for low calorie sugar on account of growing health awareness is expected to drive this market. Key players in the global mannitol value chain include Roquette, Cargill, SPI Pharma, Qingdao Bright Moon Seaweed Group, and Singsino Group. The company ZuChem has obtained a patent from the US Patent Office for fermentative production of mannitol. There are no known UK activities in mannitol production.

Epichlorohydrin is a chemical intermediate primarily used in the production of epoxy resins for coating, electronics, composites, and adhesives. Other niche markets for this chemical include surfactants for home and personal care, elastomers, water treatment chemicals and paper chemicals. The estimated market of epichlorohydrin is about 2 million tonnes per year with expected growth of 2% per year till 2020.[21] Bio-based epichlorohydrin produced from glycerol supplies about 15% of the market, with the remainder being supplied by propylene derived epichlorohydrin. Solvay has patented a bio-based epichlorohydrin process. There are no known activities on bio-based epichlorohydrin in the UK.

Ethanol consumption as a fuel accounts for more than 85% of global consumption. It can be used directly in the engine or used to make ethyl tert-butyl ether (ETBE). Ethanol is also used in cosmetics, pharmaceuticals, detergents, inks and coatings, the food and alcohol beverage industry, as well as a chemical intermediate in the synthesis of ethene, glycol ethers, ethanolamines/ethylamines, ethyl propenoate. In 2016 world fuel ethanol production was 26,583 million gallons US, and modest growth of around 2.5% per year is expected[20]. Several companies are developing ethanol from lignocellulose, and the technology is being demonstrated at commercial scale in the US, Europe and Brazil. There is limited activity on lignocellulosic ethanol production in the UK, with companies such as Fiberight and Nova Pangaea Technologies working on technology and parts of the process.

Fatty alcohols are mainly used in the production of detergents and surfactants. Other applications include cosmetics, food and industrial solvents. The global fatty alcohols market was valued at US$3.52 billion in 2014 and is expected to grow at a rate of around 5%[22]. Natural fatty alcohols are produced from plant oils and animal fats by transesterification of triglycerides and subsequent hydrogenation of fatty acids methyl esters. Synthetic fatty alcohols are produced by the Ziegler process which polymerises ethylene by using an organoaluminium catalyst. Several companies such as Codexis and LS9 have attempted to produce fatty alcohols via sugar fermentation routes, but have not resulted in commercial production. Solazyme uses dark fermentation to produce an algal oil that is then used to produce chemicals and biofuels, including fatty alcohols. The UK has well established personal and homecare and cosmetics industries which could be a potential outlet for fatty alcohol applications (surfactants).

Fumaric acid is used in the manufacture of medicines, drinks, food, animal feed, cleansing agents, unsaturated polyester, alkyd resins, and printing inks. The food and beverages segment was the largest end user of fumaric acid in 2016, accounting for 35% of world consumption. In food and beverage applications, fumaric acid serves primarily as an acidulant, where it is used to adjust pH,

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[21] Solvay 2016. http://www.ptit.org/InnoBioPlast2016/presentation/Session3/4.pdf

[22] https://globenewswire.com/news-release/2016/03/21/821569/0/en/Fatty-Alcohols-Market-to-reach-US-5-48-billion-by-2023-Boosted-by-Growth-of-Personal-Care-Industry-Global-Industry-Analysis-Size-Share-Growth-Trends-and-Forecast-2015-2023-TMR.html

enhance flavour, and extend shelf life by controlling the growth of microorganisms. Other significant end uses for fumaric acid include unsaturated polyester resins (19% of world consumption), rosin paper sizes (18%), alkyd resins (11%), and animal feed (5%). In animal feed, fumaric acid functions as an acidulant.[23] Most of the fumaric acid is sold in China or South East Asia. The market value is estimated at US$750 million, with a forecasted growth, mainly in China, of about 3.7% per year. It is produced from benzene or n-butane derived maleic anhydride feedstock. Bio-based fumaric acid can be produced by fermenting C6 sugars, and fungal fermentation using renewable sugars is at the development stage. Main bio-based developers of fumaric acid are DSM and Myriant, and there are no known UK activities.

Furfural has a broad spectrum of industrial applications, such as the production of plastics, pharmaceuticals, agro-chemical products and non-petroleum-derived chemicals e.g. furfuryl alcohol. Chemicals derived from furfural include 2-methylfuran, 2-methyltetrahydrofuran, furan, cyclopentanone, cyclopentanol, mostly used in the pharmaceutical and agro-chemical industry, which are well-developed in the UK. Other chemicals that could be derived from furfural include: succinic acid, 1,4 butanediol, and gamma butyrolactone. Furfural is produced from biomass, but current production technology has several deficiencies such as low yield, high energy use and high use of sulfuric acid[9]. Demand is expected to grow, providing a driver for technology improvement.[24]

Glucaric acid has numerous potential applications, both as a building block chemical and in direct end uses. The most important application is as detergent builder, which softens the water and prevents deposit of limescale and dirt on the surface of fabric or dishes being washed. Glucaric acid could potentially replace phosphate based detergent builders e.g. sodium tripolyphosphate (STPP), which are gradually being phased out due to environmental issues. Over 4.5 million tonnes of phosphates are sold worldwide annually for this application.[25] Other glucaric acid applications include food ingredients, concrete plasticizers, corrosion inhibitors and polymers. Glucaric acid can be converted into adipic acid which can be used for production of nylon 6,6 and other polyamide resins and polyurethanes, potentially accessing a several billion dollar market. Glucaric acid can be produced in one step from glucose by oxidation e.g. using nitric acid. However this technology has not been scaled to large industrial volumes as it produces nitrogen oxide (NOx) compounds and generates waste. Several companies have been looking into improving this glucaric acid production route as well as developing other bio-based routes. Rennovia and UK-based catalyst specialist Johnson Matthey have licensed their glucaric acid technology to the agricultural firm Archer Daniels Midland for commercialisation[26,27]. Rivertop Renewables has teamed up with Cargill to pursue the development of bio-based glucaric acid technology. An early stage biosynthetic route for production of glucaric acid is also being investigated (*Escherichia coli* fermentation of glucose).

Glycerol is used in the food industry, pharmaceuticals and personal care products, mainly as a lubricant or humectant (moisturizer). It is also used as a feedstock for conversion into chemicals such as epichlorohydrin, acrolein, citric acid and succinic acid. There are also technology developments

[23] "*Lignocellulosic Biomass: A Sustainable Platform for Production of Bio-Based Chemicals and Polymers*" Furkan H. Isikgor C. Remzi Becer, School of Engineering and Materials Science, Queen Mary University
[24] "Bio-based Chemicals: Value Added Products from Biorefineries" International Energy Agency. 2012 – 2013.
[25] http://www.soci.org/chemistry-and-industry/cni-data/2011/4/building-block-for-change
[26] https://greenchemicalsblog.com/2017/02/21/adm-enters-glucaric-acid-production/
[27] https://www.acs.org/content/acs/en/molecule-of-the-week/archive/g/glucaric-acid.html

focused on converting glycerol to advanced biofuels[28]. Other applications include production of alkyd resins, tobacco products, explosives, cellophane and detergents. Most glycerine is produced from vegetable oils or animal fats as a by-product of biodiesel production. The most common synthetic pathway is the oxidation of propene to epichlorohydrin which is subsequently hydrolysed to glycerol. The synthetic pathway is generally more expensive but it can produce higher purity product for specialty applications. The global glycerol market was valued at US$ 2.19 billion in 2015 and projected to grow at a rate of 6.8%. Technology development in the UK is focused on producing higher added value chemicals from glycerol, e.g 1,3-Propanediol, 3-Hydroxypropionic acid, succinic acid.

Isoprene is mostly (60%) used as a building block for polyisoprene rubber, styrene co-polymers and butyl rubber used for manufacturing tyres. Other applications include adhesives, medical and personal care applications. The isoprene market is estimated at a value between US$1 and US$2 billion[27], and is expected grow at a rate of 2.5%[29]. Isoprene is mainly produced from naphtha today. Bio-based isoprene, produced by aerobic bioconversion of carbohydrates, is identical to petroleum based isoprene and functions as a drop-in replacement molecule.[30] Most of the bio-based developments are driven by the automotive industry, pursuing bio-based rubber for tyres. Several companies are working on the commercialisation of bio-based isoprene: Goodyear is collaborating with DuPont and Michelin is collaborating with Amyris. Other companies developing fermentative isoprene processes include GlycosBio, Aemetis and LanzaTech. There are no known UK bio-based isoprene activities.

Itaconic acid offers the potential to replace the petroleum-based acrylic acid used in the production of superabsorbent polymers (SAP) which are widely used for production of consumer goods such as nappies and other similar personal care products. It also offers characteristics similar to maleic anhydride, so is a prospective replacement for it in the production of unsaturated polyester resins (UPR). Its market is currently small at about 80 kilotonnes per year and production is largely in China, but it has potential to tap into a market in excess of £10 billon. UK based Itaconix is one of the leading companies in the development of bio-based polymers from itaconic acid. Other UK activities include R&D work at the Universities of Nottingham and York.

Lactic acid is used to produce polylactic acid polymer (PLA), which is suitable for packaging materials, insulation foam, automotive parts, and fibres (textile and non-woven). PLA is also used in high-value medical applications like sutures and tissue scaffolds due to its biocompatibility and biodegradability. Most lactic acid is produced by microbial fermentation of carbohydrates, and a small amount is produced by chemical synthesis using acetaldehyde. The lactic acid market is estimated at about 800 kilotonnes per year[15]. Growing consumer awareness around sustainability, biodegradability, recyclability, and green packaging is expected to drive PLA usage globally, translating into a 6-8% growth rate. Natureworks is the leading lactic acid producer. Imperial College spinout Plaxica has licensed their D-Lactic acid process technology to Natureworks, and UK based

[28] http://www.inkemia.com/en/component/content/article/2-uncategorised/884-licensing-out-activity?Itemid=898
[29] https://www.ihs.com/products/isoprene-chemical-economics-handbook.html
[30] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016

Cellulac is developing a process for converting lactose whey into optically pure lactic acid (used for PLA).

Levoglucosenone can be obtained by thermocatalytic treatment of cellulose, and its derivatives can be used in applications including herbicides, flavour molecules, dispersants for graphene, solvents and biocides. Levoglucosenone can be used to make 5-hydroxymethylfurfural, dihydrolevoglucosenone (Cyrene™) as a bio-based dipolar aprotic solvent, and 1,6-hexandiol, a multimillion tonnes commodity chemical. Alternatively, it can also serve as a chiral substrate for the pharmaceutical industry.[31] UK based company Circa Sustainable Technologies is developing a continuous process to make levoglucosenone.

Levulinic acid is a precursor for pharmaceuticals, plasticisers and various other additives, e.g. delta-aminolevulinic acid is used as a herbicide, and diphenolic acid could be a replacement for bisphenol Ain the production of polycarbonates. It is also used to produce other industrial commodity chemicals such as methyltetrahydrofuran (MTHF), valerolactone, and levulinate esters. Levulinic acid can be produced by acid treatment of starch or from C6 sugars via hydration of HMF as an intermediate. A side product of this reaction is formic acid which is produced in equimolar amounts. It is also possible to obtain levulinic acid from the C5-carbohydrates in hemicellulose (e.g. xylose, arabinose) by addition of a reduction step (via furfuryl alcohol) subsequent to the acid treatment[32]. The global market for levulinic acid is relatively small, anticipated to reach US$19.65 million revenue by 2020, with a CAGR of 4.8%[33]. Companies which are involved in bio-based developments of levulinic acid technology include Biofine, DSM, Segetis, GFBiochemicals. GFBiochemicals started commercial production of levulinic acid in 2015 at a production scale of 2000 tonnes/year in Caserta, Italy. The challenge is to find high value applications for levulinic acid, which could also be an opportunity for new applications and new players to enter into this space. Aston University is researching levulinic acid.

L-Lysine is an essential amino acid, mainly used as a dietary supplement for humans, and in animal feed. Additionally, L-lysine is a bio-based precursor of caprolactam and nylon applications. Chemical, enzymatic and fermentation processes have been used to synthesize L-lysine[34]. Production by fermentation has an advantage over chemical synthesis methods as it produces only the L-form, thus eliminating the need for the expensive resolution of DL-lysine produced purely by the chemical synthesis method. Bacterial fermentation of glucose to L-lysine has been commercialised, and yeast/fungal fermentation could also be possible. Other routes currently under investigation are the development of genetically modified plants with elevated levels of certain amino acids such as L-lysine.[35]In 2011 the global demand for L- lysine was about 1.6 million tonnes, with a market value of US$3.5 billion[36]. In the near term a growth of about 4% per year is expected in the major L-lysine consuming regions[37]. The global lysine market share is fragmented and key companies include, Royal

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[31] https://presentations.acs.org/common/presentation-detail.aspx/gce2016/gc--e/gce12a/2487932?login=y
[32] "Bio-based Chemicals: Value Added Products from Biorefineries" International Energy Agency. 2012 – 2013.
[33] http://www.grandviewresearch.com/press-release/global-levulinic-acid-market?
[34] "*Fermentative production of l-lysine: fungal fermentation and mutagenesis-ii a review*" Pakistan Journal of Pharmaceutical Sciences Vol. 15, No.2, July 2002, pp.29-35
[35] "Bio-based Chemicals: Value Added Products from Biorefineries" International Energy Agency. 2012 – 2013.
[36] https://www.feednavigator.com/Article/2014/03/31/Global-BioChem-to-put-the-brakes-on-lysine-production
[37] https://www.ihs.com/products/major-amino-acids-chemical-economics-handbook.html

DSM, Cargill, Global Biochem Technology,etc.[38] Currently there is no known UK activity in the development of the bio-based L-lysine.

Malic acid is mainly used as flavour enhancer in the food industry. It is produced by double hydration of maleic anhydride. Bio-based malic acid can be synthesized by species of the fungus Aspergillus on thin stillage, a co-product from corn-based ethanol production, and on crude glycerol, a coproduct from biodiesel production[39].The global malic acid market is around 60,000 tons per year with a value of US$130 million and an estimated growth rate of 4% per year[40]. Malic acid can be converted to 1,4 Butanediol and potentially access a market of about US$2.5 billion. Industrial Microbes is developing a fermentation process to manufacture malic acid from CO2 and natural gas. In 2012 Novozymes announced they were developing bio-based malic acid. There are no known UK activities in bio-based malic acid.

Methanol is used in the chemical synthesis of many chemicals including: formaldehyde, methylamines, methyl methacrylate, acetic acid. It is also used as a fuel, blended in gasoline as methanol or MTBE, and blended in diesel as fatty acid methyl esters (FAME). Most methanol is produced by catalytic methanol synthesis from syngas, with syngas produced by methane reforming or coal gasification. Other production routes include bio-methane reforming, bio-syngas conversion, catalytic conversion of hydrogen and CO2 into methanol and fermentation of flue gases. The Dutch company BioMCN converts biogas into biomethanol[41]. The Canadian company Enerkem gasifies domestic waste to produce methanol and other widely used chemicals[42]. BioMCN operates a glycerine gasification plant in the Netherlands. Carbon Recycling International (CRI), in Iceland, produce renewable methanol by catalytic reaction of carbon dioxide and hydrogen[43]. Global methanol demand is around 95 million metric tons, and demand is growing rapidly in particular in regions such as China (7% growth).

Methylmethacrylate (MMA) is a commodity chemical with global market size of more than 4.5 million tonnes per year. The principal application, consuming approximately 80% of MMA, is the manufacture of polymethyl methacrylate acrylic plastics (PMMA). MMA is also used for the production of the co-polymer methyl methacrylate-butadienestyrene (MBS), used as a modifier for PVC. MMA is produced by several methods with the principal being the acetone cyanohydrin (ACH) route, which involves the use of acetone and hydrogen cyanide, an extremely toxic chemical. An alternative route developed by Lucite International uses ethylene, methanol and carbon monoxide which could potentially be sourced from bio-based feedstock. UK based company Lucite International produces methacrylate monomers and polymers, and is currently investigating the feasibility of a range of technologies, including fermentation, to produce methacrylate products.

[38] https://www.gminsights.com/industry-analysis/lysine-methionine-market
[39] *"Microbial Production of Malic Acid from Biofuel-Related Coproducts and Biomass"* February 2017, MDPI

Thomas P. West

[40] http://www.biofuelsdigest.com/bdigest/2015/04/30/the-does-12-top-biobased-molecules-what-became-of-them/
[41] http://www.biomcn.eu/
[42] http://enerkem.com/biofuels-and-green-chemicals/renewable-chemicals/
[43] http://carbonrecycling.is/

Muconic acid is a versatile chemical intermediate whose derivatives – caprolactam, terephthalic acid (a precursor to PET) and adipic acid — are widely used in the plastics industry, production of synthetic fibres for textiles, and acidifying agents for food. Muconic acid derivatives represent a market of more than US$22 billion[44]. Muconinic acid could potentially replace non-sustainable benzene and cyclohexane feedstock that polyethylene terephthalate (PET) (terephthalic acid) and nylon fibres (Caprolatam) currently rely on.[45] The growth in demand for muconic acid is likely to be driven by the growing demand for adipic acid due to rising consumption of nylon 6,6 in various applications and increasing demand for caprolactam from the carpet and textiles industry. Deinove, Myriant, and Amyris have been pursuing bio-based production of muconic acid followed by chemical catalytic conversion to adipic acid, with the majority of these processes having been demonstrated thus far at the bench scale.[46]

n-Butanol is used in a wide range of polymers and plastics, and as a solvent in paints and chemical stabilisers (with toxicity benefits compared to other solvents). n-Butanol can be produced by fermentation of carbohydrates or via the production of syngas from biomass gasification.[47] Dehydration of butanol gives butene which can then be reacted with ethylene in a metathesis reaction to give propylene.[48] The n-butanol market is large, estimated at about 3 million tonnes per year, and likely to grow significantly due to increasing demand for coatings, paints, adhesives, sealants, inks and solvent products. UK based Green Biologics has developed a bacterial (*Clostridium*) fermentation process for production of n-butanol and acetone from corn starch feedstock, which is currently produced in Minnesota, US. About 100,000 tonnes annually of n-butanol is produced in China using corn cobs and corn stover as a feedstock. In the UK there is a wide range of industries that are using or could potentially use butanol or its derivatives including pharmaceutical, agro-chemical and coating industries.

Polyhydroxyalkanoates (PHAs) are currently used in medical applications where biodegradability is a benefit. PHAs are easy to process. They can be blown and moulded, foamed and processed into yarns and they make excellent packaging materials, since they can be printed, sealed, and painted. Mixing with other plastics will often improve the qualities of the plastic. Thanks to its large variety (e.g. PHB, PHBV, P3HB4HB and PHBHHx[49]), PHA can substitute almost all major plastics in many of their applications: polyethylene, polypropylene, polystyrene, PVC, PET. Additionally PHAs can be processed to glues[50]. The PHA market was valued at US$70 million in 2015, projected to grow at a rate of about 5% from 2016 to 2021[51]. PHAs can be made by bacterial fermentation of sugars or lipids. Some research has been done into trying to make plants produce PHA in-situ via genetic modification. Companies producing PHAs tend to be small specialised bioplastics companies, such as Metabolix which specialises in PHA co-polymers. Together with PLA, it produces a plastic that can compete with HDPE. Bioplastech, a spin-off of the University of Dublin, produces PHA from plastic

[44] http://www.myriant.com/products/product-pipeline.cfm
[45] https://greenchemicalsblog.com/2014/05/01/qa-ava-biochem-on-5-hmf/
[46] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016
[47] "*Continuous syngas fermentation for the production of ethanol, n-propanol and n-Butanol.*" Liu K1, Atiyeh HK. Bioresour Technol. 2014 Jan;151:69-77. doi: 10.1016/j.biortech.2013.10.059. Epub 2013 Oct 23.
[48] "Bio-based Chemicals: Value Added Products from Biorefineries" International Energy Agency. 2012 – 2013.
[49] Industrial Production of PHA. Guo-Qiang Chen. 2010.
[50] https://www.biobasedpress.eu/2016/08/pha-promising-versatile-biodegradable/
[51] http://www.marketsandmarkets.com/Market-Reports/pha-market-395.html

waste through bacterial conversion. KANEKA, a major Japanese plastic producer, develops varieties with good heat-resistant properties (e.g. for plastic cups) and varieties that can be used as a biodegradable agricultural plastic. Spanish AIMPLAS develops fire-resistant PHA panels for the automotive industry[29].

Propylene glycol (PG) also known as **1,2-Propanediol** is unique among glycols as it is safe for human consumption. It is used in production of cosmetics e.g. suntan lotions and antiperspirants, in the food industry as a flavour extraction solvent, and in many personal care products such as moisturisers and emulsifiers. Other applications include: replacement of ethylene glycol as engine coolant and antifreeze, drying agent in water based coatings and feedstock for production of polyester resins for end use markets such as construction, passenger vehicles and consumer appliances. In 2016 the global propylene glycol market was estimated at about 2.2 million tonnes per year, with annual expected growth of about 4.5%[52]. Propylene glycol is produced from petroleum feedstock by hydrating propylene oxide. According to the DOE's report from 2016[27]propylene glycol price has historically always followed the price of propylene and it appears to be consistently about US$500 per tonne above the propylene price. Bio-based propylene glycol can be produced either by catalytic hydrogenolysis of glycerine feedstock, a by-product of biodiesel, or by hydrocracking of sorbitol produced from glucose. Belgium-based oleochemical firm Oleon operates a glycerine-to-PG facility. The glycerine feed is a co-product of the biodiesel and oleochemical operations that use animal fats and vegetable oils as feedstock. German-based BASF developed and licensed the bio-based PG production process and supplies the catalysts. The facility in Ertvelde, Belgium has a capacity of 20,000 tonnes. Other active companies include US based ADM which runs the only glycerine-to-PG facility located in the United States and Chinese Global Bio-Chem which produces about 200,000 tonnes annually of propylene glycol from corn derived sorbitol[53].

p-Xylene is primarily used as a raw material in the manufacture of terephthalic acid (TPA), purified terephthalic acid (PTA) and dimethyl-terephthalate (DMT). TPA, PTA and DMT are used to manufacture polyethylene terephthalate (PET) saturated polyester polymers used in drinks bottles and polyester fibres. The paraxylene market is large. In 2015 it was estimated at about 37 million tonnes with an expected growth rate of 6%[54]. Paraxylene is produced by cracking naphtha or by crude oil refining. A wide range of bio-based p-xylene production routes are under development including fermentation followed by upgrading, thermochemical pyrolysis routes, and hybrid thermochemical/ catalytic upgrading of sugars. Feedstocks used in these routes range from utilizing all of the biomass or portions of the biomass including carbohydrates and lignin. Businesses which are pursuing bio-based p-xylene include Gevo, and Micromidas aiming for selective p-xylene production, while Virent, Anellotech and Biochemtex are developing routes aimed at reformate production. These technologies are currently at the pilot or demonstration scale. There are no known UK activities related to the development of bio-based p-xylene.

[52] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016
[53] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016
[54] *"The latest technologies designed to meet paraxylene market opportunities"* K.A. Couch, C. Beterlli, UOP/Honeywell. 2015.

Succinic acid's primary applications include the production of agricultural chemicals, coatings and inks, corrosion inhibitors, solvents, detergents, metal plating, and biodegradable polymers e.g. polybutylene succinate (PBS). The succinic acid market is small about 20 to 50 kilotonnes per year[55], with a primary focus on specialty chemicals. The projected market for biomass-derived succinic acid is large however, with succinic acid as a possible precursor for the synthesis of high-value products including commodity chemicals, polymers, surfactants, and solvents. Petroleum derived succinic acid is produced from C4 hydrocarbons or maleic anhydride. Bio-based succinic acid is produced via biological conversion of biomass-derived intermediates including sugars, glycerol, and cellulosic sugars. Several companies are developing bio-based succinic acid, including BASF, Corbion, DSM, Roquette, BioAmber, Myriant. There are no known UK activities in relation to succinic acid.

Terpenoids are a broad class of related chemicals, commonly found in plants at very low concentrations. They have applications such as flavours, fragrances, and therapeutics. The market size and value will vary from product to product but ranges from kilograms to thousands of tonnes and from US$1000/tonne to US$1000/kg. The complexity makes a biosynthetic route to production competitive compared to chemical synthesis[56] . The volumes at which terpenoids are produced would make it easier to establish a supply chain in the UK compared to commodity chemicals. There are however no known activities in the UK at present..

Xylitol is an important outlet of xylose as it is a popular sweetener for the food and pharmaceutical industries. Xylitol is becoming more popular due to consumer awareness of its health benefits over sugar; it has all the sweetness of sugar but with 40% less calories.[57] The conventional method for producing xylitol is via hemicellulose which is extracted from biomass (corn cobs or hardwood), hydrolysed to xylose and catalytically hydrogenated to xylitol. There is limited commercial production of xylitol outside China; total production is estimated at 900,000 tonnes per year[58].Conventional xylitol production has high energy requirements, extensive purification steps and high product cost, and may face a threat from sugar polyols such as sorbitol, mannitol and maltol[59]. There are companies targeting more efficient bio-based production of xylitol e.g. S2G BioChem. There are no known UK activities related to the development of bio-based xylitol.

[55] "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential." Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin. National Renewable Energy Laboratory 2016
[56] Green Biologics (2017), personal communication
[57] "Bio-based Chemicals: Value Added Products from Biorefineries" International Energy Agency. 2012 – 2013.
[58] "Bio-based Chemicals: Value Added Products from Biorefineries" International Energy Agency. 2012 – 2013.
[59] https://www.gminsights.com/industry-analysis/xylitol-market

4 Framework for determining UK bio-based chemicals opportunities

An approach was developed to systematically rank bio-based chemicals and identify the most promising development opportunities for the UK. It is based on a prioritisation matrix that assesses the market attractiveness and the UK's strengths for the investigated bio-based chemicals.

The prioritisation matrix, shown in Figure 4-1, shows four types of actions that are linked to the relative market attractiveness and the UK strength of any bio-based chemical. **Focus** and **Invest to Improve** represent attractive markets and will contain bio-based chemicals that represent business and value opportunities for the UK. The **Opportunistic** area is less attractive for the UK because the global market has limited value and/or strong established competition, despite the UK strengths for the relevant bio-based chemical. However, there could be ad-hoc opportunities for creating valuable markets and strengthening the UK position as well as developing opportunities related to new products or applications based on the bio-based chemicals in this quadrant. Bio-based chemicals in the **Lower Priority** area are unlikely to be of interest though niche opportunities may exist.

STRONG

UK Strengths
A function of UK activities, capabilities and potential to create value related to the specific bio-based chemical

WEAK

Opportunistic The UK is well positioned for these bio-based chemicals, but the market is less attractive. The UK could take advantage of these as a stepping stone to other products.	**Focus** The UK should provide focused support to build upon existing strengths to seize attractive market opportunities.
Lower Priority Less attractive opportunities and the UK as a whole is not well positioned. There may still be opportunities for individual organisations.	**Invest to improve** The UK could invest to improve positioning since these are attractive from a market perspective but currently hard to attain.

Market Attractiveness. A function of market size, market growth potential, ease of access and risk/barriers related to the market of the specific bio-based chemical

LOW ⟷ **HIGH**

Figure 4-1 Prioritisation matrix for determining the top bio-based chemicals opportunities for the UK

4.1 Approach to assessing market attractiveness and UK strengths

A consistent and transparent approach to assessing Market Attractiveness and UK Strengths for each bio-based chemical is fundamental to populating the prioritisation matrix and meeting the main objective of this study.

4.2 Market attractiveness

Market attractiveness is influenced by different factors that impact it in different ways. The challenge was to find proxies for market attractiveness that can be applied to a broad list of bio-based chemicals while maintaining consistency in terms of data quality and availability for the 30+ chemicals that were investigated in this study. The list of these chemicals (see Table 3-1) is very mixed; containing commodity chemicals that are produced in large quantities at relatively low cost as well as specialty chemicals with small production volume but relatively high market prices.

The following proxies for market attractiveness were selected, bearing in mind the differences mentioned above:

- Market Size (Value),
- Market Growth Potential,
- Competitiveness and Market Access, and
- Interesting Features (of the bio-based chemicals).

The data used to quantify these proxies is presented in section 3.

4.2.1 Market size (Value)

The measure of this proxy is the current global market value. For chemicals that have undeveloped markets, the market size was estimated based on the potential derivatives and replacements of petroleum based products. A Low-Medium-High scoring scale is used for scoring based on the estimated market value for the chemical considered. This market value represents the theoretical size for the bio-based chemical to replace its mainstream alternative.

Table 4-1 Market Size (Value)

Score	Market Size
Low	< US$500m
Medium	US$500m to US$10bn
High	> US$10bn

4.2.2 Market growth potential

This proxy is related to the prospective market growth of the chemical that could be replaced by the bio-based alternative. The measure of this proxy is projected compound annual growth rate (CAGR). Where information about market growth was not conclusive, CAGR was estimated by considering market drivers for the investigated chemical or product, expected changes of these drivers over time, and/or expected market growth of derivatives and downstream applications of the bio-based chemical.

Table 4-2 Market Growth Potential

Score	Market Growth Potential
Low	CAGR < 5%
Medium	5% <CAGR < 10%
High	CAGR >10%

4.2.3 Competitiveness and market access

Competitiveness and market access was measured by the level and strength of existing competitors and barriers to entering the market. These depended on the number and the type of key players who are involved in the production or development of the bio-based chemical; the level and type of partnerships between technology developers and producers of the bio-based chemical; and the technology development stage and intellectual property (IP) landscape.

Table 4-3 Competitiveness and Market Access

Score	Competitiveness and Market Access
Low	Difficult: Large multinational companies involved in the development or production of bio-based technology, holding IP related to technology and products, with strong partnerships with other multinationals or technology developers .
Medium	Moderate: A few bio-based players at the early stage of product development with some partnerships across the value chain.
High	Easy: Few or no bio-based players at the early stage of development with no strong partnerships.

4.2.4 Interesting features

Interesting product features or functionalities could create a market pull and increase market attractiveness. For this proxy we evaluated whether a bio-based chemical has interesting or advanced features, especially compared to its petroleum derived analogue, and how important these features can be to the market. Features include improved performance; environmental impact; (bio)degradability; lower toxicity; GHG emissions; and more energy- or cost-effective production processes.

Table 4-4 Interesting Features

Score	Interesting Features
Low	No advantages compared to petroleum derived alternatives
Medium	At least one interesting feature or advantage compared to petroleum based alternatives
High	Significant advantages and advanced features compared to petroleum based alternatives

4.3 UK strengths

For **UK strengths** the following proxies have been selected:

- UK industry and academia activity,
- UK industry and academic capability to develop relevant technology, and
- Potential of the UK to create an integrated supply chain.

The data used to quantifying these proxies is presented in section 3.

4.3.1 Industry and academic activity

The intensity of industry and academic activity was measured, i.e. more activity provides momentum and a foundation to build upon. For example, academic research related to a development of metabolic pathways for production of a specific bio-based chemical provides a good opportunity to create exclusive knowledge in this area that may be protected and converted into monetisable licences; partnerships with UK industry could also be initiated for technology development and manufacturing.

Table 4-5 Industry and Academic Activity

Score	Industry and Academic Activity
Low	No evidence of any activity or only one (isolated) academic activity related to the specific bio-based chemical
Medium	Evidence of more academic partners and some industrial partners working on the specific bio-based chemical (2 – 5 actors)
High	Evidence of intense academic and industry activity focused on the specific bio-based chemical (> 5 actors)

4.3.2 Industry and academic capabilities

The extent of Industry and Academic Capabilities was measured, i.e. to what extent do industry and academia possess the skills, knowledge and infrastructure to support the development of pathways, technology, and product derivatives for a bio-based chemical. For example, evidence of skills and capabilities related to the development of thermochemical conversion technology (e.g. syngas catalysis) is considered as beneficial for any bio-based chemical that is obtained through thermochemical pathway. The same applies to the existence of relevant research foci, e.g. relevant technology development centres and pilot facilities.

Table 4-6 Industry and Academic Capabilities

Score	Industry and Academic Capabilities
Low	Little or no evidence of capabilities: the UK has no or very limited skills, know-how or infrastructure relevant to the development and production of the bio-based chemical.
Medium	Some evidence of capabilities: the UK has some skills, know-how or infrastructure relevant to the development and production of the bio-based chemical.
High	Clear evidence of capabilities: the UK has most or all skills, know-how or infrastructure relevant to the development and production of the bio-based chemical.

4.3.3 Potential for supply chain integration

The potential to develop an integrated supply chain was measured, i.e. whether there is only an opportunity to create a specific sector activity in the UK (e.g. technology licensing or research) or whether the UK can develop an integrated supply chain by which several players across the value chain benefit and add value for the UK.

Table 4-7 Potential for Supply Chain Integration

Score	Potential for Supply Chain Integration
Low	No opportunities for UK production and integration into downstream products
Medium	Limited opportunities for UK production and integration into downstream products
High	Good opportunities for UK production and integration into downstream products

5 Prospective UK bio-based chemicals and case for growth

The prioritisation matrix shown in Figure 5-1, synthesises the assessment of the bio-based chemicals considered in relation to their Market Attractiveness and the UK strengths. The scoring matrix for the bio-based chemical opportunities is given in Appendix A (Figure 5-2).

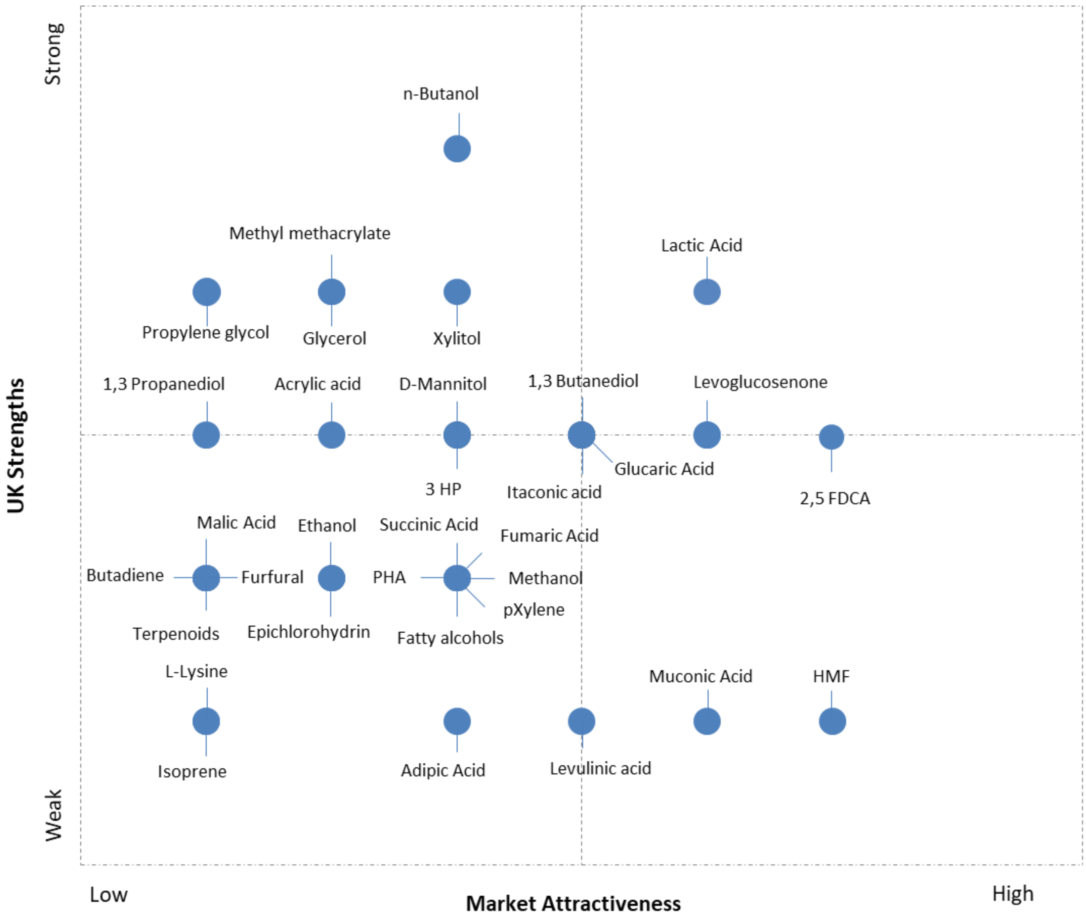

Figure 5-1 Results of the list of bio-based chemicals assessment for the UK Legend: 3-HP (3-Hydroxypropionic acid), HMF (5-Hydroxymethylfurfural), PHA (Polyhydroxyalkanoates), p-Xylene (Paraxylene), FDCA (2,5 Furandicarboxylic acid)

The assessment leads to the following tentative list of top bio-based chemicals development opportunities for the UK:

1. Lactic acid
2. 2,5-Furandicarboxylic acid (FDCA)
3. Levoglucosenone
4. 5-Hydroxymethyl furfural (HMF)
5. Muconic acid
6. Itaconic acid

7. 1,3-Butanediol
8. Glucaric acid
9. Levulinic acid
10. n-Butanol
11. Xylitol
12. 3-Hydroxypropionic acid (3-HP)
13. D-Mannitol
14. Polyhydroxyalkanoates (PHA)
15. Fatty alcohols
16. Fumaric acid
17. Succinic acid
18. p-Xylene
19. Methanol
20. Adipic acid

The list of top bio-based chemicals for the UK is neither definitive nor exhaustive. It is a snapshot and a preliminary assessment of bio-based chemical market opportunities and the current positioning of the UK in relation to them.

Priority is given to those bio-based chemical opportunities which appear to have greatest market attractiveness i.e. positioned in the right half of the matrix. Although the UK may not be in a strong position in relation to the development of some of these opportunities, in most cases this can be improved by building on the existing activities and capabilities.

The results of the analysis show that there is a range of bio-based chemicals with good market opportunities, and where the UK could position itself competitively based on existing activities specifically related to the bio-based chemicals in question.

Lactic acid is used in the production of degradable polyesters, such as PLA, and has large market potential as a result of growing environmental concerns and government regulations related to the use of petroleum derived, non-renewable plastics. The UK has a competitive position in lactic acid development, with UK based companies, such as Plaxica and Cellulac, having successfully generated value from lactic acid technology development, licensing and manufacturing.

2,5-Furandicarboxylic acid (FDCA) has a large market potential associated with the displacement of petroleum derived chemicals in various polymer applications, such as polyethylene terephthalate (PET), as a result of demand for sustainable plastics with enhanced functionality. FDCA derivatives have a number of interesting features which include degradable plastics and polymers, as well as improved functionality compared to their petroleum derived alternatives. The UK has good strengths in FDCA development, with several academic and commercial activities on FDCA, including the University of Liverpool, the University of York, the University of Manchester, and Biome Bioplastics. Besides developing pathways to produce FDCA from biomass, the activities also focus on production of novel polyester polymers with advanced functionalities.

Levoglucosenone is attractive as a high value ingredient in the pharmaceutical, flavour, fragrance and pheromone industry and for its conversion into commodity chemicals used for the production of solvents and polymers, which could provide safer and healthier alternatives to existing solvents. Few companies are developing levoglucosenone, and the UK is in a relatively good position with respect to commercialising the production of levoglucosenone and its derivatives through, for example, the activities of UK based company Circa Sustainable Chemicals UK.

Similarly to FDCA, **5-Hydroxymethyl furfural** (**HMF)** is attractive due to its versatility in producing new homo and co-polymers with advanced functionalities and improved degradability. These polymers could replace petroleum derived alternatives in elastomer, adhesive and coating applications, thus opening up a large market. Few companies are currently working on the development of HMF technology globally, and in the UK activities are focused on research, for example at Imperial College and at the University of Liverpool.

Muconic acid has a large market potential as it can be converted to a variety of chemicals and polymers. Currently there is no commercial production of muconic acid. The potential replacement of benzene and its derivatives in many polymer applications, such as polyethylene terephthalate (PET) and nylon fibres, makes muconic acid important in terms of sustainability. The development of new downstream applications and polymers from muconic acid is a key opportunity area. Well established synthetic biology and polymer science capabilities in UK universities and industry position the UK well for muconic acid technology development.

Itaconic acid could access large markets by replacing petroleum derived chemicals in many applications such as superabsorbent polymers (SAP) and unsaturated polyester resins (UPR). Although several large companies are engaged in the development of itaconic acid, the technology is still at an early stage, leaving space for other developers. The UK has strengths in relation to itaconic acid, with industrial and academic activities related to its development and that of its polymer derivatives, including activities at Itaconix, the University of York and the University of Nottingham.

1,3-Butanediol (1,3-BDO)could access large markets through its conversion to chemicals such as 1,3 butadiene. Industrial and academic activity in the UK is focused on clostridium fermentation technology, an area in which the UK is strong. Furthermore, the UK has the potential to create an integrated supply chain for production of 1,3-BDO for specialty product applications.

Glucaric acid has a potentially large opportunity as a replacement for phosphate builders in detergent applications, where environmental regulation is driving a move away from phosphates, creating an opportunity for this chemical to tap into the large personal and home care market. Johnson Matthey's work on scaling up of bio-based glucaric acid provides a competitive position for the UK in relation to this chemical.

Levulinic acid is attracting interest from chemical companies as a source of green solvents and for the production of polymers with advanced functionalities, which could replace petroleum derived plastics. Levulinic acid technology relies on the pretreatment and thermochemical conversion of biomass, but the UK lacks strength in scaling up and demonstrating these technologies.

The **n-Butanol** market is large and could potentially grow in the near term mainly due to increased consumption as a solvent in formulated products and as a feedstock for synthesis. Very few players currently work on the commercialisation of lignocellulosic butanol, and the UK is well positioned, with several industrial activities related to technology development, and scale up.

The UK is also well positioned for the development of chemicals such as **methylmethacrylate**, **acrylic acid**, **D-Mannitol**, **xylitol**, **3-Hydroxypropionic acid** and **glycerol**, though their market attractiveness is lower. For example, in the case of acrylic acid or glycerol there is strong competition from other bio-based producers of these chemicals, and chemicals such as D-mannitol or xylitol have relatively small markets and modest growth outlooks.

For the remaining bio-based chemicals on the list, the current market outlook does not seem to be attractive for new bio-based players to enter. In some cases, e.g. furfural or malic acid, the markets are generally small and expect relatively low growths. Fatty alcohols have a relatively larger market, however the fermentation based technology is still at the early stage and will compete with well-established technology which is already based on biomass feedstocks: vegetable oils and animal fats. Other bio-based chemicals such as succinic acid or adipic acid are actively pursued by large multinational companies leaving little space for new players to enter, and the UK does not seem to be in a strong position in relation to technology development or creating value from these chemicals.

5.1 Case for growth

Overall, there is a range of promising bio-based chemicals with good market opportunities as a result of improved functionality and greater sustainability. The development of these bio-based chemicals and their derivatives is still at a stage where it is possible to innovate and compete, and the UK has promising strengths and capabilities. The economic value of the markets that could be accessed by these bio-based chemicals is very large. There is therefore a strong rationale for investing in this area, though investments should follow more careful and detailed assessments of the technical and economic prospects of the specific bio-based chemical production pathways.

Globally, governments and private companies are already providing support and investing in the transformation of the chemical industry. A public private partnership between the EU and the Bio-based Industries Consortium is investing about 3.7 billion Euros (2014 to 2020) in R&D and innovation, aiming to replace at least 30% of petroleum-based chemicals and materials with bio-based and biodegradable ones by 2030. Furthermore, most of the large chemical and pharmaceutical producers have sustainability high on their agendas. Many of them are setting ambitious targets of becoming 100% carbon neutral and considerably improving the sustainability of their products in the mid to long term to 2050. To achieve these targets businesses are improving sustainability through their entire value chains by considering: sustainable feedstock for their products, decarbonising manufacturing and reducing the environmental impact of the product end-of-life and disposal. Companies like Coca Cola and Lego are putting significant investment into making their products from 100% bio-based plastics. Lego is currently building a Sustainable

Materials Centre in Denmark, which will comprise 4,000 square meters of research facilities and employ about 100 people when it opens in 2018.

The UK is one of the world's top global producers of chemicals and pharmaceuticals. According to the UK's Office of National Statistics (2014/2015), the chemical and pharmaceutical sector was the largest export earner. This sector exported goods worth a total of £50 billion with more than half of this value coming from the chemical industry. The gross value added (GVA) by the chemical industry was approximately £8.8 billion in 2014/15. In 2014 the chemical industry employed 105,000 people.[60,61,62] Investing in the bio-based chemicals sector would contribute to the sustainable growth of the UK's chemical industry and potentially generate significant added value to the UK economy. Additional growth of the UK's chemical industry by a few percentage points could generate hundreds of millions of pounds in gross added value and thousands of jobs.

In the UK the value is likely to arise from different parts of the value chain depending on the products. Although significant job creation and economic impact comes with manufacturing, the UK may not be strongly positioned for the manufacturing of large quantities of bio-based chemicals. Native feedstock (biomass) availability and feedstock prices are likely to limit the potential of manufacturing bio-based chemicals in the UK, especially drop-in commodity type bio-based chemicals which are often needed in larger volumes, above 100 kilotons per year. Thus for the UK, the opportunity may mostly be in the manufacturing of specialty type of bio-based chemicals which have high market value and relatively low volume demands e.g. 5 to 20 kilotons per year. These bio-based chemicals could fit well within the UK's supply chain, both from the feedstock supply and integration into downstream sectors.

But, to create value from bio-based chemicals the UK does not necessarily need to manufacture them. Significant value is likely to arise from different parts of the value chain and business models, which include licensing of technology and exporting services and knowledge. Synthetic biology, biocatalysis, chemistry and polymer R&D capabilities are well established in the UK. This provides a competitive advantage to the UK with respect to creating IP in this area, which could potentially be monetised through selling technology licenses and services.

Bio-based chemicals could lead to environmental benefits in the UK, with reduced carbon emissions being one important dimension of the environmental benefits. These will depend on the end-of-life of the products, but benefits could be substantial especially through cascading uses of bio-based products eventually through to energy recovery. Also, the benefits will depend on the feedstock used, but could be high especially for lignocellulosic and waste feedstocks.

5.2 Path forward

The UK should provide focused support, building on existing strengths, to seize attractive market opportunities for bio-based chemicals. The focus should be on the development of innovative bio-based products which will be able to outperform traditional fossil-based products by providing sustainability characteristics in line with strong sustainability drivers and enhanced product

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[60] https://www.themanufacturer.com/articles/chemicals-industry-uk-manufacturings-unique-element/
[61] UK Chemical and Pharmaceutical Industry Facts and Figures" Chemical Industry Association, 2015.
[62]https://www.ons.gov.uk/businessindustryandtrade/business/businessservices/bulletins/uknonfinancialbusinesseconomy/2015revisedresults

characteristics. Improved functionality and value will result in a strong end-users driver. For example, new engineered plastics like PEF reduce carbon footprints in the food packaging sector, but also outperform polyethylene terephthalate (PET) in oxygen barrier performance and improved processing. Displacing fossil-based commodity products with bio-based equivalents will be challenging, requiring economies of scale that might be difficult to achieve, especially in the UK. However, there is potential for bio-based products to be competitive with fossil alternatives.

While sustainability requirements are growing, it is unlikely that bio-based chemicals will command significant price premia longer term, unless there is a regulatory requirement or incentive or they provide improved functionality. Policy support which incentivises the development and use of bio-based chemicals is necessary to accelerate market uptake. For example, the UK has no policy that incentivises the use of degradable materials or plastics in consumer applications, while in January 2017 France introduced a policy which mandates the use of home compostable materials for all single-use supermarket bags and food catering packaging, leading to an increase in demand for compostable resin. As a result, the Italian firm Novamont has already revitalized five decommissioned plants and has partnered with the Barbier Group, France's largest plastic film manufacturer, to develop improved home-compostable film[63].

Interviews indicated that UK companies are often looking for technology testing and scale up services outside the UK, and that there is a demand for open access piloting and demonstration facilities able to provide affordable services to the UK's bio-based sector. In particular, technology advances in feedstock pretreatment and the supply of low cost renewable sugars will be an important enabler for the development of bio-based chemicals. UK capabilities are fairly limited in this area, including testing and scaling up of the pretreatment technologies.

Overall, seizing opportunities in the bio-based chemicals sector will need to rely on a wide range of supporting activities including research programmes and funding, the facilitation of networks and collaborations, the establishment of open access piloting and demonstration facilities, investment in piloting, demonstration and early stage companies, as well as demand side measures.

[63] http://www.packagingdigest.com/sustainable-packaging/france-prompts-huge-potential-for-compostable-packaging-growth-2016-11-21

Appendix A Scoring matrix for bio- based chemicals opportunities

Market attractiveness scoring

Scoring of the "Market Attractiveness" proxies is described in section 4.2. Numerical values 0, 1 and 2 are assigned to the scoring qualifiers "Low", "Medium" and "High", respectively. See Table 4-1, Table 4-2, Table 4-3 and Table 4-4.
The overall score for market attractiveness is calculated by averaging the score of all the proxies: Market Size (Value), Market Growth Potential, Competitiveness and Market Access, and Interesting Features (of the bio-based chemicals).

UK strengths scoring

The scoring approach for the "UK strengths" proxies is described in section 4.3. Numerical values 0, 1 and 2 are assigned to the scoring qualifiers "Low", "Medium" and "High", respectively. See Table 4-5, Table 4-6 and Table 4-7.
The overall score for UK strengths is calculated by averaging the score of all the proxies: Activity, Capability and Potential (to create integrated supply chain).

Chemical	Market Attractiveness				Total score Market Attractiveness	UK Strengths			Total score UK Strengths
			Ease of access						
	Market value	Market Growth	Market Competitiveness	Interesting features		Activity	Capabilities	Potential (to create integrated supply chain)	
1,3 Butanediol	1	0	2	1	1.00	1	1	1	1.00
1,3 Propanediol	1	0	0	0	0.25	0	1	2	1.00
3- Hydroxy propionic acid	1	1	1	0	0.75	1	1	1	1.00
Acrylic acid	1	1	0	0	0.50	1	1	1	1.00
Adipic acid	1	1	0	1	0.75	0	1	0	0.33
Butadiene	1	0	0	0	0.25	1	1	0	0.67
D-Mannitol	0	0	2	1	0.75	0	1	2	1.00
Epichlorohydrin	1	0	1	0	0.50	0	1	1	0.67
Ethanol	2	0	0	0	0.50	0	1	1	0.67
Fatty alcohols	1	1	1	0	0.75	0	1	1	0.67
FDCA	2	2	0	2	1.50	1	1	1	1.00
Fumaric acid	1	0	1	1	0.75	0	1	1	0.67
Furfural	0	0	1	0	0.25	0	1	1	0.67
Glucaric acid	1	1	0	2	1.00	1	1	1	1.00
Glycerol	1	1	0	0	0.50	1	2	1	1.33
5- Hydroxymethylfurfural	1	1	2	2	1.50	0	0	1	0.33
Isoprene	1	0	0	0	0.25	0	1	0	0.33
Itaconic acid	1	1	1	1	1.00	1	1	1	1.00
Lactic acid	1	2	1	1	1.25	2	1	1	1.33
Levoglucosenone	1	1	2	1	1.25	1	1	1	1.00
Levulinic acid	0	1	1	2	1.00	0	0	1	0.33
L-Lysine	1	0	0	0	0.25	0	1	0	0.33
Malic acid	0	0	1	0	0.25	0	1	1	0.67
Methanol	2	1	0	0	0.75	0	1	1	0.67
Methyl methacrylate	1	0	1	0	0.50	1	2	1	1.33
Muconic acid	1	1	2	1	1.25	0	1	0	0.33
N-butanol	1	1	1	0	0.75	2	2	1	1.67
Polyhydroxy alkanoates	0	1	1	1	0.75	0	1	1	0.67
Propylene glycol	1	0	0	0	0.25	0	2	2	1.33
para Xylene	2	1	0	0	0.75	0	1	1	0.67
Succinic acid	0	2	0	1	0.75	0	1	1	0.67
Terpenoids	0	0	1	0	0.25	0	1	1	0.67
Xylitol	1	0	1	1	0.75	1	1	2	1.33

Figure 5-2 Scoring matrix for bio-based chemicals opportunities