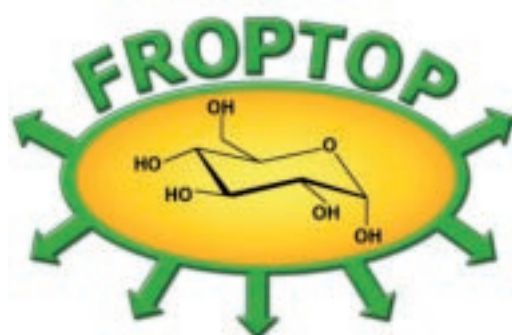


UK Expertise for Exploitation of Biomass-Based Platform Chemicals

A white paper by
The FROPTOP Group





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This paper was produced under the FROPTOP banner. FROPTOP (From Renewable Platform Chemicals to Value Added Products) is a joint special interest group of Bioscience for Business, Chemistry Innovation, the Royal Society of Chemistry, and the Institution of Chemical Engineers that works with industry, academia, government and other networks to develop the market for renewable chemicals in the UK.

FROPTOP covers renewable, biomass-derived chemicals and their use in chemical and biochemical processes. The aim of the group is to identify the portfolio of products that can be derived from biomass-based chemicals and also the tools needed to convert these renewable chemicals in a sustainable way.

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1. Scope of the white paper



Biomass offers an attractive alternative to fossil-based feedstocks as a source of energy, materials and chemicals. For the production of chemicals, the sugars (mostly in the form of cellulose or hemicellulose), lignin and oils that are present as the main components of plants can be extracted and processed into industrial intermediates or products.

This white paper provides an overview of current UK expertise in the production and conversion of biomass-based chemicals into products. It also presents a rationale on why the use of biomass as a chemicals feedstock could be advantageous for UK businesses and for the wider population. The paper focuses on the technologies that can generate useful chemicals for industry and includes a number of case studies to illustrate the conversion of biomass-based feedstocks. Outside the remit of this paper are activities in the optimisation of plants as renewable feedstocks, the processing of biomass to enhance conversion to platform chemicals, plants as sources of macromolecules (fibres, resins etc.) and biofuels.

The purpose of this paper is to provide an overview of activities in the UK renewable chemicals market. It is not a full market assessment with the aim to identify key market areas and products.

In addition to identifying key experts, the technology mapping exercise included in this paper may help industrialists and policy-makers to identify current capabilities, technology gaps and the barriers to adoption that prevent further take-up by the chemicals sector. It is based on research performed by four organisations working closely with the UK's chemistry-using and chemicals industries: Bioscience for Business Knowledge Transfer Network, Chemistry Innovation Knowledge Transfer Network, the Royal Society of Chemistry and the Institution of Chemical Engineers under the banner of the FROPTOP (From Renewable Platform Chemicals to Value Added Products) Special Interest Group. Assistance was provided by the Centre of Excellence for Biocatalysis, Biotransformations and Biocatalytic Manufacture. A workshop has been organised at which the opportunities, gaps and barriers of the UK renewable chemicals market were discussed by the identified experts. The outcomes of these discussions are included in this paper. The FROPTOP team would like to thank all contributing parties for their input (see Appendix 4 – Acknowledgements).

2. Background




Fossil fuel sources provide the majority of feedstocks for chemicals manufacture and the industry is already reacting to their increased costs. In April 2008, leading chemical companies announced price increases of the order of 20 – 25% for their speciality materials as a consequence of higher fossil fuel prices. Current volatility in the price of fossil fuels continues to have a major impact on the chemicals industry.

Chemicals derived from biomass have the potential to form the foundation of a huge range of products coming from the chemicals industry. A transition to renewable chemical feedstocks offers a number of advantages: the prospect of a better economic return through reduced feedstock costs, environmental benefits through lower carbon emissions and an improved opinion of the chemicals industry by the general public. The chemicals industry often suffers a poor reputation with the public through a combination of concerns over pollution (e.g. through emissions or effluent discharge), health risks and standards of plant safety. However, a growing desire from consumers for green products and sustainable development presents an excellent opportunity for the chemicals industry to re-engage positively with the public through the development of a renewable chemicals market. This engagement should emphasise the sustainability and positive life cycle impact of renewable chemicals and clearly demonstrate the case for responsible manufacturing.

Traditional petrochemical industry feedstocks for the chemical industry are based around a relatively low number of hydrocarbon-based platform chemicals. A similar approach could be applied to chemicals derived from biomass where a small number of sugar-, oil- or lignin-based chemicals are used as simple intermediates in traditional chemical processing. Several reports have identified a number of building block chemicals produced from biomass via biological or chemical conversions (see Appendix 1 - Potential building blocks derived from biomass)¹.

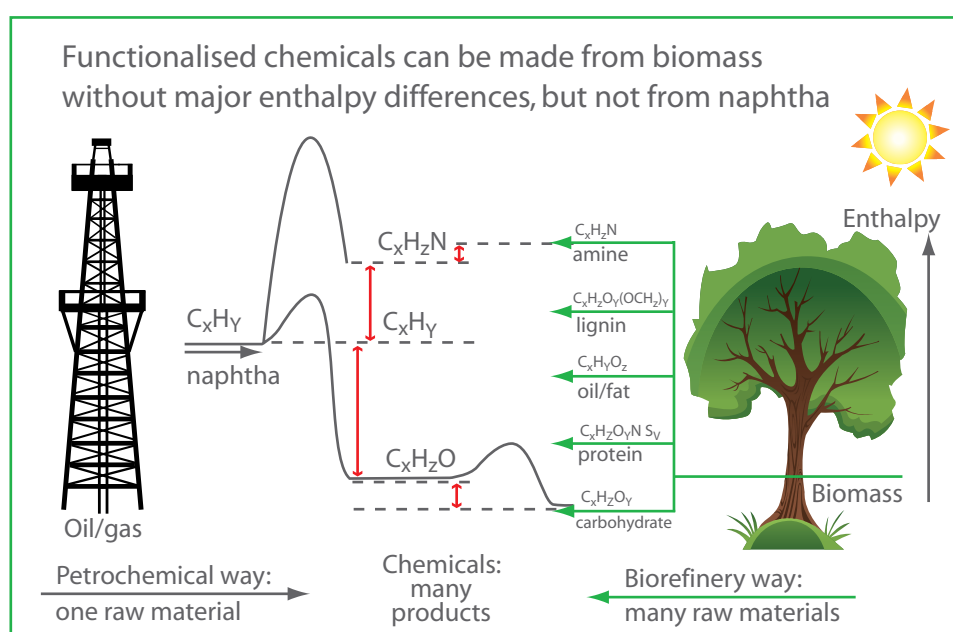
The use of biomass-derived chemicals represents an area with extensive R&D potential for the development of renewable, feedstock-based technology platforms. Improvements and innovations to existing biological and chemical processing of sugars, fats, oils and lignin will provide opportunities for the production of high-value chemicals and products from biomass and reduce the reliance on petrochemical-derived products.



¹(a) Volume I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas. Pacific Northwest National Laboratory and the National Renewable Energy Laboratory, 2004; (b) Top Value Added Chemicals from Biomass Volume II: Results of Screening for Potential Candidates from Biorefinery Lignin. Pacific Northwest National Laboratory and the National Renewable Energy Laboratory, 2007 (c) Medium and Long-term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources – The Potential of White Biotechnology – The BREW Report, Utrecht September 2005)

3. Markets for Renewable Platform Chemicals

The market for renewable chemicals is growing, driven by consumer demand and governmental policy². With the advent of REACH, some chemicals will effectively be removed from the market providing chemicals manufacturers with an opportunity to provide innovative substitutes based on renewable feedstocks. The markets most likely to exploit bio-based platform chemicals as raw materials include polymers (e.g. packaging), solvents (e.g. printing), resins (e.g. inks) and surfactants/detergents. The initial major impact is expected for the personal care and polymer industries where a number of bio-based products are already in production today.



Energy Barriers to Chemicals from Feedstocks³

3.1 Bio-based Chemicals in the Personal Care Market

Consumer goods represent a major area for early adoption of renewable chemicals with desire for 'natural' products growing strongly amongst consumers. Major retailers such as Marks & Spencer are now stating their intention to move towards a carbon neutral status and are demanding improvements to the sustainability credentials of their products. The fast moving consumer goods sector, which has a long history of developing products containing plant extracts and renewable materials and often within short development times, is seen as an important early adopter. Sustainable replacements for a number of ingredients used in personal care formulations are being sought (see Appendix 2 - Potential sustainable replacements for ingredients for personal care formulations)⁴.

²Creating Value from Renewable Materials – A strategy for non-food crops and uses. Two year progress report' DEFRA/DTI, November 2006

³J. P. M. Sanders et. al. Macromol. Biosci. 2007, 7, 105-117 DOI:10.1002/mabi.200600223

⁴List courtesy of Boots UK Limited

3.2 Bio-based Chemicals in Polymer Production

The production of bio-based polymers is an emerging sector of polymer industry. From a traditional base utilising starch and cellulose as raw materials, the industry is turning its attention towards synthetic polymers based on renewable raw materials.

Niche markets such as food packaging are already served by products like polylactic acid (PLA), which is derived from bio-based lactic acid. Constant improvements in the downstream processing of PLA are allowing the penetration of new markets and applications.

In terms of production volume, ethylene derivatives dominate the plastics industry. Global ethylene consumption amounted to 109 million tons in 2006, feeding the polyethylene, ethylene oxide, styrene, polyvinylchloride, and a number of other supply chains. The production of bio-based ethylene to supply these chains is the target of a number of companies (see Case study 1).

Case Study 1: The Production of Renewable Polyethylene

In 2007, Dow Chemical announced it was forming a joint venture with Crystalsev to make polyethylene from sugarcane ethanol. That venture will build a new facility and expects to start production in 2011.

Case study 2: The Production of 1,3-propanediol (PDO), the key building block for DuPont™ Sorona® polymer

In 2006 DuPont and Tate & Lyle announced the first commercial shipments of Bio-PDO™ from its facility in Loudon, Tennessee, USA. The facility produces 1,3-propanediol (Bio-PDO™) from renewable resources (corn sugar) making it the first in the world to manufacture this new bio-based product.

Away from ethanol-based production, the rapid development of industrial biotechnology is increasingly allowing cost competitive monomer production. The use of industrial biotechnology for monomer production has been demonstrated by Du Pont and Tate & Lyle (see Case study 2).

A number of platform chemicals have attracted the attention of polymer producers. Succinic acid can be converted to 1,4-butanediol (BDO) or tetrahydrofuran (THF), which allows the production of bio-based poly(butylene terephthalate) and poly(tetramethylene ether glycol). The acrylic acid market for the production of superabsorbent polymers (e.g. for nappies) is the focus of groups working on 3-hydroxypropionic acid fermentation. Fumaric acid serves as a building block for two important classes of polymers: unsaturated polyester resins (UPRs) and alkyd resins.

There are substantial market opportunities in both the personal care and polymers markets but also in many other chemicals-using industries from which the UK could benefit if the right expertise and resources were available. To assess the extent and nature of this UK expertise base is the principal aim of this paper.

4. Current UK activities



Full details on UK expertise in Renewable Chemicals can be found in Appendix 3.

4.1 Available Expertise at UK Research Organisations

The UK has a strong history in biotechnology research. It is very strong in:

- using isolated enzymes
- biocatalysis
- bio-prospecting
- utilizing the functionality of molecules
- chemical transformations


However, research so far was often focussed on applications not closely connected to biomass-based platform chemicals: for example development of pharmaceuticals. Apart from that a number of UK academic centres have active research programmes encompassing the use of biomass-based platform chemicals.

Case study 3: Research on Renewable Polymers

The Williams group at the Department of Chemistry, Imperial College London is working on the development of polymers from renewable resources and is conducting research in the following areas:

- Preparation of polylactide from lactide using low toxicity catalysts and initiators;
- Synthesis of entirely new polyesters from carbohydrates (patents have recently been filed). These polyesters are highly hydrophilic and much more rapidly degradable than PLA. Also, they are sourced from lignocellulosic biomass rather than corn/starch which is needed for PLA;
- Synthesis of polycarbonates by copolymerisation of carbon dioxide and epoxides;
- Synthesis of polycarbamates (polyurethanes) by copolymerisation of carbon dioxide and epoxides;
- Synthesis of nylon derivatives by ring opening polymerisation of β -lactams derived from aspartic acid;
- Catalytic transformation of carbohydrates into small molecules. This work centres on developing homogeneous catalysts which enable the dehydration of pyranoses to occur at room temperature and with good selectivity.

One of the main areas of research is in catalysts for polymerising biomass-based monomers into biopolymers such as PLA, and subsequent chemistry to improve the properties of these materials (Case study 3). There is activity in this area at the Universities of Edinburgh, Bath, Bangor, Warwick and York and at Imperial College London. Some academics are looking at traditional chemical transformations and the catalysts needed to convert oxygen-rich platform molecules into commercial ingredients and intermediates. Work in this field is underway at Bath, York, Warwick, Nottingham, and Cardiff universities and Queens University Belfast.



The use of biocatalysts to transform platform chemicals into functional products is more widespread with activity at Cranfield, Newcastle, Exeter, Leicester, Sheffield Hallam, York and Bath universities. Fermentation routes are also being examined at the universities of Teesside, Manchester and Warwick. Although much of this work focuses on carbohydrate and oil-based building blocks, some work is also underway on lignin.

These university-based research efforts are spread across chemistry, chemical engineering and bioscience departments but there are several important centres of excellence also helping to develop this technology area:

- The Satake Centre for Grain Process Engineering, Manchester
- Centre for Sustainable Chemical Technologies, Bath
- BioComposites Centre, University of Wales, Bangor
- Green Chemistry Centre of Excellence, York

4.2 Available Expertise in UK Industry

Relatively few companies could be identified that produce biomass-based chemicals. Significantly more activity could be identified in the biofuels sector where the feedstocks and biochemical processes are often similar. Green Biologics, an SME based in Oxfordshire, works on the development of integrated fermentation processes for the production of both biofuels and biochemicals. A small number of commercial organisations work on the conversion of renewable platform chemicals (C-Tech Innovation, Centre for Process Innovation, Croda). Downstream processing methods are also being developed by several companies (e.g. EKB Technology, C-Tech Innovation, CPI and Green Biologics). However, very few organisations have the facilities to demonstrate these new processes at a commercial scale with the exception of Croda and CPI.

4.3 UK Industry using biomass-based chemicals

There are a number of UK companies which are already making use of renewable chemicals in their products. These companies operate mainly in the consumer product markets (Croda, Kemcare, Unilever, Boots), the coatings market (AkzoNobel, Arizona Chemicals, Croda) or the polymers market (Lucite International, Industrial Copolymers, Warwick International, Lake Chemicals & Minerals). One company develops the use of biomass-based chemicals in solvents (Bioniqs).

The list of companies in Appendix 3 is restricted to examples of UK companies using renewable chemicals. There are significantly more UK companies in the consumer products market which incorporate bio-based chemicals into their products but most of these use chemicals extracted directly from plants and are therefore outside the scope of this paper. The list of companies processing biopolymers also has potential to expand. Those companies included in Appendix 3 were selected due to their high levels of activity in converting biomass to chemicals or because of their impact on the renewable chemicals market due to company size.

5. Discussion



The mapping of renewable chemicals expertise presented in this paper has shown that there are a number of key activities in renewable chemicals within the UK. There are several active research programmes encompassing the use of biomass-based platform chemicals. Several of them are supported by industry. A number of industrial users of biochemicals also exist in the UK. In addition, there are a significant number of companies which could potentially apply renewable chemicals to their processes. One of the first industrial sectors to address to use of renewable chemicals would be polymers production (e.g. Ineos - ethylene for LLDPE and Invista - adipic acid).

Consumer Goods companies may lead innovation in using biomass-based products as they have a short lead time to market for their products. They would prefer the biomass-derived chemicals to be identical to those they already use to avoid issues of having to test a new product. Other areas of industry have problems when changing the material of a product as they require relatively long periods of testing. For example anti-corrosion coatings need to be tested for more than five years before the product can come onto the market.

One of the most important future markets for biomass-based chemicals will be the existing speciality chemicals market. Industry prefers to use chemicals already known to them, and which have a proven safety track record. The chemical origin does not matter (e.g. it doesn't matter whether lactic acid is from petrochemicals or renewable sources as long as it is chemically identical). Industry will use chemicals made from biomass-based resources but they will need to be price and performance competitive with existing products. The issue of sustainability still comes behind price and performance for most manufacturers when designing a product. However, some biomass-based materials may be able to command a price premium for applications such as food packaging where the sustainability of a product is being used as a marketing tool.

The market for renewable chemicals will continue to grow driven by consumer demand and governmental policies that aim to generate sustainable development and reduce carbon emissions. Substantial returns from the production of renewable chemicals are achievable in the future through the combined impacts of higher oil prices, better process technologies and changes in policy and regulation. In addition, potential benefits are available to the chemicals industries, agriculture and downstream producers through the generation of employment opportunities and attraction of inward investment to build new infrastructure.

The UK has a strong foundation of expertise existing within the area of renewable chemicals. This base of expertise is comprehensive but tends to be dispersed quite thinly across academia and industry. Industrial biocatalysis activity is often focused abroad but chemical catalysis is well established in the UK (e.g. Davy Process Technology, Johnson Matthey). There is also significant expertise in chemical and biochemical engineering, which is of high importance for process development. Collaborative and interdisciplinary research is required to tackle the challenges of the development of a renewable chemicals industry. The FROPTOP special interest group aims to act as a national focus point for renewable chemicals by connecting across this expertise base and, through its membership, to help to define the strategic development of this sector to the overall benefit of UK industry.

Academia needs a steer from industry on what chemicals need to be made and for what purpose. In the UK there is a lack of resources for developing academic research towards industrial use. This is a significant barrier to industrial acceptance for a lot of research. The nature of development of processes to produce biomass-based chemicals means an industrial focus is essential. This funding/technical/philosophical gap may cause problems, however it may also present an excellent opportunity to improve technology transfer in this area.

Given the established base of expertise in renewable chemicals available in the UK, there are enormous opportunities for developing the production capability of this sector in the UK. However, better exploitation of this expertise base is required to enable the translation of research activity into viable demonstration projects and full-scale biorefining operations. For example, there is currently no production-scale capability for producing polymers from bio-based chemicals in the UK.

6. Conclusions & Recommendations



FROPTOP believes that the best opportunities to increase the number of renewable specialty chemicals lies in the conversion of renewable bulk chemicals to specialty products. It is not necessary to grow all the biomass feedstocks in the UK. Biomass-based chemical feedstock can be imported and converted in this country into higher value chemicals. It is important to think globally to allow technology to flourish, but eventually carrying out all stages locally will be a necessity.

As the base of expertise tends to be dispersed irregularly across the academia and industry, a national focus point to combine this expertise and develop the renewable chemicals market is required.

Interdisciplinary research is of extreme importance for the development of the renewable chemicals market. Disciplines of importance include biology, microbiology, biochemistry, molecular biology, chemistry, engineering and informatics. Interdisciplinary research should therefore be strongly supported by the appropriate funding bodies.

An integrated technology supply chain is needed. If a stage in the supply chain is missing, then the UK needs to either: create that stage, or create a venture with a country that can facilitate that stage; otherwise the supply chain will reach a bottleneck and will not follow through to completion.

Academia needs a steer from industry on what chemicals need to be made from biomass and for what purpose. To develop meaningful biomass-based processes and products the UK needs to build better connections between academia and industry.

Significant expertise in related science and technology areas (e.g. biopharmaceuticals, and biofuels) exists in the UK. Many of the organisations involved in such research and development have not considered applying their expertise to the production of biomass-based chemicals; but these organisations could be important sources for knowledge transfer into the renewable chemicals sector.

Appropriate funding routes are required to support research into the area of renewable chemicals, especially for academic research groups. In particular, funding for academic research aimed towards industrial use is required. This would present an excellent opportunity to improve technology transfer in this area.

Public support is required to facilitate the transfer of research results into industrial processes. The renewable chemicals market is not the only one in the UK which faces this problem, but it is a high-risk market which very often involves a significant change of industrial infrastructure. Financial assistance in technology transfer and large-scale demonstration will reduce the risk for industry.

There is a need for people with multidisciplinary training, trained in collaboration with industry. More and better training should be provided in the fundamentals of sustainability, life cycle, economics and business, both for those studying for PhDs and those at undergraduate level too.

Although the social and environmental impacts of bio-based chemicals often compare very favourably to petrochemical-based chemicals, the associated financial risks often discourage uptake by industry. Targeted policy measures to reduce financial risk would have a stimulating impact similar to those already in place to support the uptake of renewable materials in energy production.

Development of processes and products based on renewable chemicals has to be accompanied by an assessment of their economic and environmental impacts to ensure their sustainability. However, these assessments should not hinder development. Meaningful but manageable tools for Life Cycle Analysis are required.

Education will be needed to make downstream users of renewable chemicals aware that these chemicals might have different properties but they can also offer economic and environmental benefits.

7. Appendices



Appendix 1 - Potential building blocks derived from biomass

Carbohydrates

Sugars can be transformed into chemicals with multiple functional groups that have a high transformation potential into new families of useful molecules. However, sugars can also be used to replace traditionally used chemicals derived from fossil resources (see case study 1). Examples of sugar-based platform chemicals are ethanol (C2), glycerol (C3), succinic acid (C4), xylitol (C5) and sorbitol (C6).

Oils and fats

Oils and fats are already well established as biomass-based chemicals in industry. The oleochemical industry uses over 16 million tonnes of oils and fats worldwide. Its products range from food applications (e.g. emulsifiers), metal working (e.g. cutting oils) to electronics (e.g. wire insulation)⁵. A variety of chemical and enzymatic reactions are used to transform oils and fats into basic oleochemical substances like fatty acids, fatty acid methyl esters (FAME), fatty alcohols, fatty amines and glycerols, which can be further converted into chemical intermediates like alcohol ethoxylates, alcohol sulfates, alcohol ether sulfates, quaternary ammonium substances, monoacylglycerols (MAG), diacylglycerols (DAG), structured triacylglycerols (TAG) and sugar esters.

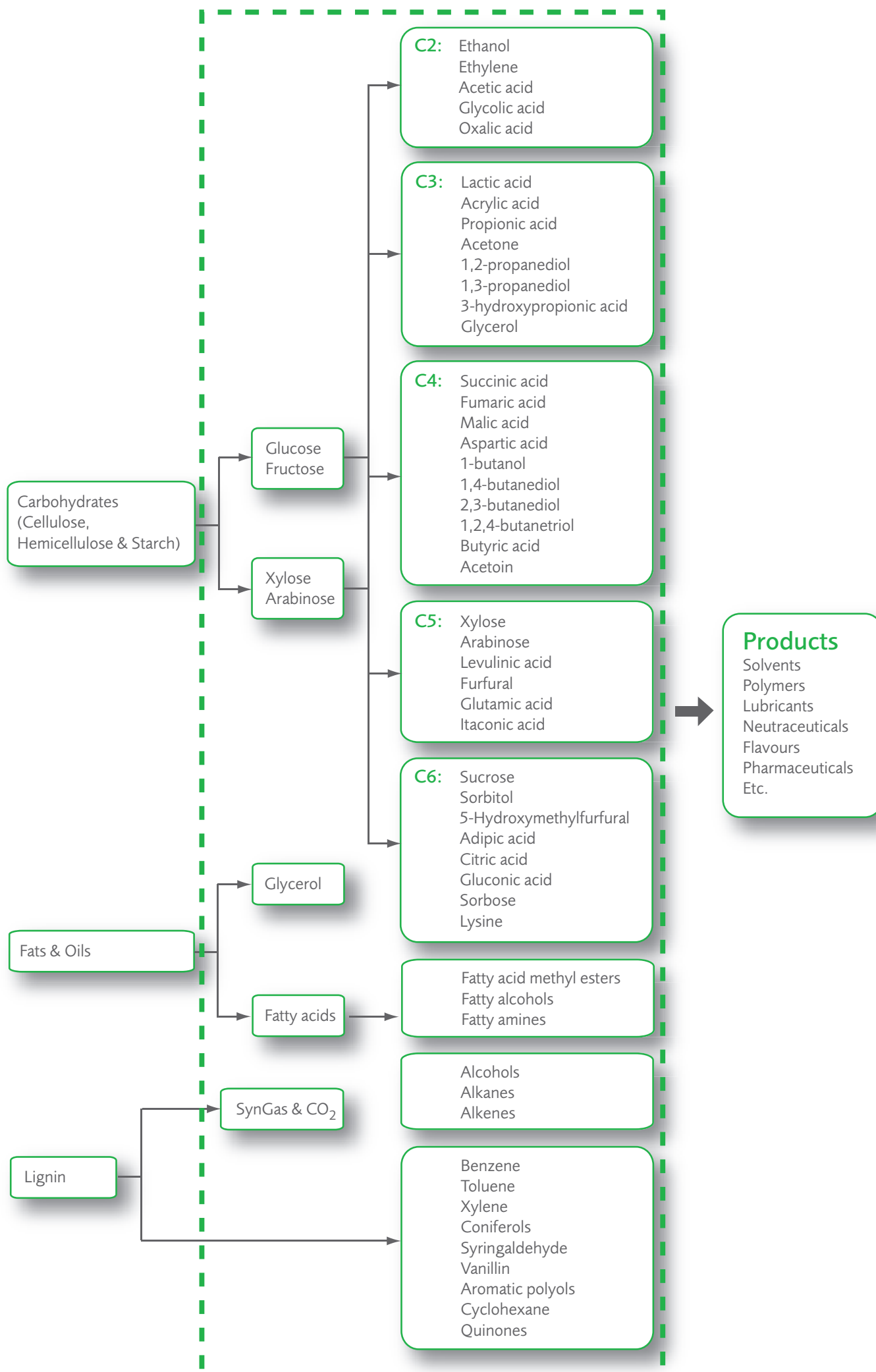
Lignin

Another product from biomass-based processes is lignin. At the moment it is mainly used to produce process heat by combustion or in animal feeds. But lignin has also the potential to be a chemical feedstock. It can be used as a carbon source by gasification producing syngas (carbon monoxide/hydrogen), which can be transformed into methanol, dimethyl ether, olefins and mixed alcohols (ethanol and higher value alcohol chemicals). In addition lignin can be converted into aromatic hydrocarbon products that could or are already used commercially (e.g. phenol or vanillin).

A list of biomass-based building blocks can be found on the next page.



⁵ 'Oleochemical Manufacture and Application', Frank Gunstone and Richard J. Hamilton, October 2001, Wiley-Blackwell



Appendix 2 - Potential sustainable replacements for ingredients for personal care formulations

Detergents

Salts of ethoxylated fatty alcohol sulphates or alkylpolyglucosides (APGs)

- Available from a sustainable source and is fully biodegradable
- Non-irritant and non-sensitising
- Do not use ethylene oxide for ethoxylation
- Do not require preservation in aqueous solutions
- Good foam properties – a wide-open bubbled foam
- Good detergent properties
- Can be thickened – but not necessarily using the normal thickener (NaCl)

Emulsifiers

- Polyglycerylestere
- Any sugar ester - the type of sugar is not important
- Low HLB (hydrophilic/lipophilic balance) polyglyceryl ethers/esters

Rheology Modifiers

- Polyacrylates or natural thickening agents

Preservatives

- To avoid legislative issues only molecules that exhibit preservative properties as a secondary function could be considered
- Anything that enhances the efficacy of any current legally allowed preservative, thus reducing the total preservative level.
- Glycols – humectants with secondary preservative function.

Emollients

- Primarily fatty acid esters.

Volatiles

- Silicones
- Ethanol

Appendix 3 - UK Expertise in Renewable Chemicals

Expertise in Academia:

Organisation	Department & Contact Name	Renewable building blocks used	Technology	Products
Carbohydrate based				
Cranfield University	School of Applied Sciences <i>Dr. Raffaella Villa</i>	alcohols	biocatalysis	
Sheffield Hallam University	Biomedical Research Centre <i>Dr. Tom Smith</i>	alkenes	monooxygenase biocatalysts	chiral epoxides
The University of Edinburgh	School of Chemistry <i>Dr. Polly Arnold</i>	lactic acid	catalytic polymerisation using chiral lanthanide complex	PLA
Imperial College London	Department of Chemistry <i>Dr. Charlotte Williams</i>	lactic acid; aspartic acid, carbohydrates	polymerisation techniques	PLA, polyesters, nylon
Queen's University Belfast	School of Chemistry and Chemical Engineering <i>Dr. Andrew Marr</i>	1,3-propanediol	transition metal catalysts	amines
University of York	Green Chemistry Centre of Excellence <i>Prof. James Clark</i>	succinic acid and other platform molecules	chemical synthesis	esters, amides, succinimides, pyrrolidones etc.
University of Nottingham	Department of Chemistry <i>Prof. Martyn Poliakoff</i>	itaconic acid	decarboxylation in supercritical water	methacrylic acid
University of Teesside	School of Science & Technology <i>Dr. Pattanathu Rahman</i>	glucose	throughput fermentation technology & process optimisation	glycerol, succinic acid, ethanol
University of Bath	Centre for Sustainable Chemical Technologies <i>Prof. Matthew G. Davidson</i>	diols, polyols, lactides, glycolides, sugars	main group and transition metal catalysts	biodegradable polymers, materials precursors, fine chemical feedstocks
University of Newcastle upon Tyne	Institute for Cell and Molecular Biosciences <i>Prof. Harry Gilbert</i>	carbohydrates	enzymes including glycoside hydrolases, glycosyltransferases	
The University of Manchester	Satake Centre for Grain Process Engineering <i>Prof. Collin Webb</i>	carbohydrates	Fermentation	Succinic acid
University of Bath	Centre For Extremophile Research <i>Dr. David Hough</i>	carbohydrates	biocatalysis using thermophiles	Pyruvate, Glycoaldehyde
University of Exeter	Biocatalysis Centre <i>Prof. Jenny Littlechild</i>	carbohydrates	biocatalysis using thermophiles	Chiral alcohols, carbohydrates
Queen's University Belfast	School of chemistry and Chemical Engineering <i>Prof Robin D. Rogers</i>	carbohydrates	chemical conversion	
University of Newcastle upon Tyne	School of Chemical Engineering and Advanced Materials <i>Dr Adam Harvey</i>	carbohydrates	Intensified bioreactors	Succinic acid, biopolymers, bioethanol

Fats & Oils based

University of Warwick	Department of Chemistry <i>Dr. Andrew Clark</i>	plant oils	chemical synthesis	Plastics such as polyurethane
Cardiff University	School of Chemistry <i>Prof. Graham Hutchings</i>	glycerol	supported gold and gold palladium alloy catalysts for oxidation	
Cranfield University	School of Applied Sciences <i>Dr. Raffaella Villa</i>	glycerol	biocatalysis	
University of Teesside	School of Science & Technology <i>Dr. Pattanathu Rahman</i>	glycerol	biocatalysis	Biosurfactants
The University of Manchester	Centre of Excellence for Biocatalysis, Biotransformations and Biocatalytic Manufacture <i>Dr. Gill Stephens</i>	glycerol	fermentation technology	1,3-propanediol; propionic acid; butyric acid
University of York	Green Chemistry Centre of Excellence <i>Prof. James Clark</i>	plant oils & glycerol	green chemical modification	oligomers and other products
University of Bath	Centre for Sustainable Chemical Technologies <i>Prof. Matthew G. Davidson</i>	triglycerides, unstaured fatty acids	main group and transition metal catalysts	biodegradable polymers, materials precursors, fine chemical feedstocks
University of Leicester	Department of Biochemistry <i>Prof. Gordon Roberts</i>	fatty acids	enzymatic oxidation using P450	hydroxy-fatty acids
University of Bangor	BioComposites Centre <i>Dr Paul Fowler</i>	vegetable oils		bioplasticisers & bioresins
Warwick HRI	Genomics Resource Centre <i>Dr. Guy Barker</i>	plant oils	fermentation	Biopolymers, mineral oil replacements

Lignin

University of Nottingham	Department of Chemistry <i>Prof. Martyn Poliakoff</i>	lignin	selective oxidation in water	
Queen's University Belfast	School of Chemistry and Chemical Engineering <i>Prof. Chris Hardacre</i>	lignin	chemical catalysis	
University of Warwick	Warwick HRI <i>Dr. Guy Parker</i>	lignin	degradation	phenolics
University of York	Green Chemistry Centre of Excellence <i>Prof. James Clark</i>	lignin	oxidation and other chemistries	Vanillin etc.

Syngas & CO₂

University of Newcastle upon Tyne	School of Chemistry <i>Prof. Michael North</i>	CO ₂	catalytic insertion into epoxides	cyclic carbonates
University of Newcastle upon Tyne	Institute for Nanoscale Science and Technology <i>Prof. Galip Akay</i>	Syngas	fermentation technology	Ethanol

Expertise in UK Industry:

Company	Renewable building blocks used	Technology	Products
Carbohydrate based			
Green Biologics Ltd	carbohydrates	fermentation technology	butanol
C-Tech Innovation Ltd	glucose	electrodialysis based separation system	butyric acid, lactic acid, butanol
EKB Technology Ltd	arbohydrates	electrokinetic bioreactors	organic acids
The Centre for Process Innovation (National Industrial Biotechnology Facility)	carbohydrates	fermentation	polymers, flavours
Fats & Oils based			
C-Tech Innovation Ltd	fatty acids	enzymatic processes	cosmetic esters

UK Industry applying renewable chemicals:

Company	Renewable building blocks used	Products
Lucite International		methacrylic acid
Bioniqs Ltd	acetic acid, propionic acid, glycolic acid	ionic liquids
Industrial Copolymers Ltd	rapeseed oil	bioresins
Warwick International Ltd	fatty acid	plasticisers
Arizona Chemicals	fatty acids	polyamides used in adhesives, inks and coatings
Croda	fatty acids	coatings, industrial oils
Kemcare Ltd	fatty alcohols and glucose	APGs (alkyl polyglycosides) for non-ionic surfactants and emulsifiers
Lake Chemicals & Minerals Ltd	PLA	compostable films
AkzoNobel	castor oil	coatings
Unilever	fatty acids, carbohydrates	surfactants, structural polymers
Boots	fatty acids, carbohydrates	surfactants, structural polymers
Boots	fatty acids	surfactants
Paragon Print & Packaging	PLA	Food packaging
Amcor Food Packaging	PLA	Food packaging
Sidaplast	PLA	polymer films

Appendix 4 - Acknowledgements

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Andrew Marr	Queen's University Belfast
Angus Swinscoe	Boots Technical Centre
Galip Akay	Newcastle University
George Britovsek	Imperial College London
Gill Stephens	The University of Manchester
Guy Barker	University of Warwick
Jenny Littlechild	University of Exeter
José Richardson	BERR
Kay McClean	C-Tech Innovation
Kristine Cherry	BBSRC
Matthew G. Davidson	University of Bath (Centre for Sustainable Chemical Technologies)
Merlin Goldman	Technology Strategy Board
Michael North	University of Newcastle upon Tyne
Pattanathu Rahman	University of Teesside
Polly Arnold	University of Edinburgh
Preben Krabben	Green Biologics
Steven Cartlidge	ecoLake

Glossary



Biomass – "Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood wastes and residues, plants (including aquatic plants), grasses, residues, fibers, and animal wastes, municipal wastes, and other waste materials." (Biomass Research and Development Act of 2000 7 USC 7624 Note.)

Bio-based Chemicals – Chemicals produced from biomass

Biocatalysis – the use of isolated enzymes and/or micro-organisms as biocatalysts to conduct chemical reactions

Biocatalyst – a substance, especially an enzyme, that initiates or modifies the rate of a chemical reaction [often] in a living body." Micro-organisms, including bacteria and fungi (e.g., yeasts), can also be used as biocatalysts. (American Heritage Dictionary)

Biochemicals – see 'Bio-based chemicals'

Biofuels – Liquid fuels and blending components produced from biomass (plant) feedstocks, used primarily for transportation. (PCAST, The Energy Imperative Technology and the Role of Emerging Companies, November 2006, Glossary.)

Biomass-based chemicals – see 'Bio-based chemicals'

Biomass-derived chemicals – see 'Bio-based chemicals'

Biopharmaceuticals – medical drugs produced using biotechnology

Biopolymers – polymers produced from a biological feedstock

Bioreactor – a vessel in which is carried out a chemical process which involves organisms or biochemically active substances derived from such organisms

Biorefineries – a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals.

Biotechnology – the integrated application of natural and engineering sciences for the technological use of living organisms, cells, parts thereof and molecular analogues for the production of goods and services. It consists of the use of living organisms or parts thereof, to make or modify products, improve plants and animals, or develop micro-organisms for specific purposes.

Building blocks – Chemicals that are subsequently converted to other chemical products

Detergent – a material intended to assist cleaning

Electrodialysis – the transport of salt ions from one solution through ion-exchange membranes to another solution under the influence of an applied electric potential difference

Electrokinetic – refers to the relative motions of charged species in an electric field

Emollient – substances that soften and soothe the skin

Emulsifier – a substance which stabilizes an emulsion

Enzymes – biologically-derived, biodegradable proteins that speed up chemical reactions

Fermentation – the use of micro-organisms to convert organic compounds

Green chemistry – the design of chemical processes and products with the goal of reducing or eliminating the consumption or generation of hazardous or toxic substances

Industrial biotechnology – the application of modern biotechnology for the industrial production of chemical substances and bioenergy, using living cells and their enzymes

Ionic liquid – a salt in which the ions are poorly coordinated, which results in these solvents being liquid below 100°C, or even at room temperature

Monomer – a small molecule that may become chemically bonded to other monomers to form a polymer

Oleochemicals – chemicals derived from biological oils or fats

Petrochemicals – chemical products made from raw materials of petroleum or other hydrocarbon origin

PLA – 'polylactic acid', a biodegradable, thermoplastic, aliphatic polyester derived from renewable resources, such as corn starch or sugarcane.

Plasticiser – an additive that increase the plasticity or fluidity of the material to which it is added

Platform chemicals – see 'Building blocks'

Preservative – a natural or synthetic chemical that is added to products such as foods, pharmaceuticals, paints, biological samples, wood, etc. to prevent decomposition by microbial growth or by undesirable chemical changes

Renewable chemicals – see 'Bio-based chemicals'

REACH – 'Registration, Evaluation, Authorisation and restriction of Chemicals' is a new European Union Regulation, EC/2006/1907 of 18 December 2006, which addresses the production and use of chemical substances, and their potential impacts on both human health and the environment.

Rheology modifier – a substance which, when added to an aqueous mixture, increase its viscosity without substantially modifying its other properties, such as taste

Thermophile – an organism which thrives at relatively high temperatures, between 45 and 80 °C

Volatile – a substance that is readily vapourised