The predominating factor that will influence the demand of new products for the foreseeable future will be the relative cost of fossil fuel feedstocks.

C. Governance

Greater multidisciplinary collaboration between scientists across disciplines should be enabled by bespoke funding sources. A big challenge for the chemical science community is that some chemists lack awareness of the many research opportunities in biomass conversion nor do that have an understanding of where they can play a role. IBTI and CIRC clubs offer a useful template upon which support for waste valorisation initiatives could be modelled. Both the SPIRE Public Private Partnership (PPP) and BRIDGE Horizon 2020 initiatives will be important opportunities for supporting multidisciplinary research and commercialisation at the European level.

A secure and long-term policy and regulatory framework is needed that reaches beyond 2020 to at least 2030 to provide certainty and stability for researchers and companies seeking to exploit bio-waste as a feedstock. Government legislation must encourage the use of bio-waste for value-added products including chemicals, materials and fuels, and NOT solely for energy generation *via* incineration.

Since much of the relevant regulation affecting businesses is shaped at the EU level, participation in discussions at European level is crucially167(i)5(ni)6(t)-4(i)5(ati)-8ia TmeTportant

A. Science and technology

1. What research is underway to enable high-value products to be derived from bio-waste and waste gas feedstocks and what problems could this help to solve?

The concept of , or adding value to the waste stream in an economically viable manner, -value -value product) from seawater, however extracting it from seawater is extremely expensive and the profit margin is therefore low or negative. Care needs to be taken not to exaggerate the bio-waste opportunities that could be realised using currently-available technology.

For a comprehensive review of the current situation and global perspective of food waste valorisation, including 2nd generation food waste valorisation and re-use strategies, please see the recent 2013 review article in *Energy & Environmental Science*.[1]

Bio-waste Opportunities

Sources of biomass should not compete with the crops required to provide food for an increasing world population. For this reason, *waste* biomass is an attractive and viable option as a potential substitute feedstock to fossil fuels.[2]

Conventional food-waste processing traditionally involves incinerating for energy recovery, conversion to animal feed or composting. These processes, however, miss the large opportunity to exploit the molecular complexity that exists in bio-waste for value-added products. Bio-waste materials should be considered a *resource* rather than *waste*.

Bio-waste and waste gas feedstocks offer the opportunity to dependency on fossil fuels for generating useable energy and for diversifying the feedstocks used to produce materials and commodities such as pharmaceuticals, agrochemicals, polymers and other materials. Abundant volumes of waste are generated in the UK (almost 300M tonnes each year), containing a huge diversity of functionalised chemical components, including sugars, lignin and oils, many of which cannot be found in traditional petrochemical feedstocks. There is a significant opportunity to utilise these components for higher value applications, for instance in polymers for packaging, solvents for printing, resins for inks, and as surfactants/detergents.

A large body of international research has been undertaken to exploit bio-waste over the past 20 years (see *Appendix 3)*, dominated recently by an interest in biofuels and platform chemicals (chemicals that are subsequently converted to other chemical products).

Potential Uses of Bio-waste

Sugars, oils and other compounds in bio-waste can be converted into platform chemicals directly. These building block chemicals have a high transformation potential for conversion into new families of useful molecules such as lubricant, flavours, nutriceuticals, solvents, polymers and pharmaceuticals.[3]

Some food chain wastes and co-products (e.g. spent grain from brewing) could have the potential for exploitation in the agri-food chain as sources of food ingredients such as flavours, preservatives and thickening agents. However, the *Novel Foods (EC 258/97)* legislation requires extensive investment in the testing and evaluating of new ingredients, and this could discourage investment in such activities. The existing animal feed market for these materials means that the additional financial value that could be obtained from their valorisation may not be par

Food grade wastes (e.g. vegetable and fruit trimmings, wheat bran) have the potential to provide sources of economically useful food ingredients, including:

flavourings and colourings;
bioactive compounds with health benefits such as prebiotics;
sources of dietary fibre with texture-conferring properties;
polysaccharides that might be used in the development of fat replacements, emulsifiers and stabilisers.

It is also possible to produce lower value, but larger volume products such as high quality horticultural growing materials

3. **Is it environmentally and economically viable to make use of such technologies using waste as a feedstock?**

Supply Chains

Regionally distributed sites for local processing are required. Bio-

There is significant interest within the scientific community in specialised *non-food* crops for biomass feedstocks. However, with some current technologies, significant quantities of the plant cannot be utilised. There is a particular opportunity to use sugar, lignin and oil residues for other purposes, and to develop new catalytic and fermentation processes to exploit underutilised material (see *Appendix Two*).

There are many initiatives emerging to burn wood and grasses for fuel, but these miss the opportunities to extract useful chemicals from these materials prior to incineration. There is a major opportunity for the UK to develop world-leading, innovative technologies that can further exploit a range of bio-waste feedstocks for chemicals, materials and fuels.

Microbial processes continue to require improvement.

processors, where the volume of waste is sufficient to create the much needed economies of scale that are required for low value, high volume activities.

Some bio-based products show superior functional properties compared with synthetic products in a number of applications, such as thickening agents used in a number of industries and various personal care product additives. An example of a company currently developing such products is *Sederma* (part of the *Croda International Group*). The availability of new and novel bio-based products also gives additional market and application potential. There is no doubt that the use of bio-based materials (particularly by the consumer-facing big-brand owners) is becoming an increasingly attractive marketing tool.

The UK Market

The UK has a unique opportunity to develop and undertake studies of proof-of-concept technologies because of the many different types of food that are imported and the consequent diversity of UK food waste streams. Citrus waste, brewers spent grain and apple pomaces are some examples of waste streams that could be utilised in the UK, because they are generated by many of our food companies.[5]

The exploitation of bio-waste for value-added products will rely on a robust Industrial Biotechnology (IB) sector. Therefore any factors, initiatives or recommendations relating to strengthening the UK IB sector will be important.

See *Appendix 4* for a list UK companies with current or potential interest in bio-waste valorisation.

International Perspective

Countries such as the US, Germany, Japan and China have for many years embraced the use of IB as an enabling technology and there are signs that the UK sector is now strengthening. The EU has taken a very active role in promoting IB. The European Commission set up an *Advisory Group for Bio-based Products* in 2008, which made a number of recommendations based on the assumption that one third of chemicals in 2030, including bio-polymers and bio-

The now defunct Defra LINK scheme has been cited as an excellent example of an initiative which supported pre-competitive research and development, by enabling research scientists with an interest in innovation to develop the necessary research. Through LINK, Defra provided grants to consortia of the private sector and the research base to conduct research for industrial or private sector purposes aligned to Defra objectives. This embraced Food Science programmes, which included research on bio-waste valorisation. Partly as a consequence of this, the UK already has a thriving research and development sector for IB and there are five major pilot facilities spread across the UK, offering expertise in scale-up and commercialisation of processes (see *Appendix One*). In the North East of England, the *National Industrial Biotechnologies Facility (NIBF)* at the *Centre for Process Industries (CPI)* offers process expertise and fermenters from 20 to 10,000 litres scale. These can be used by companies to ensure processes work robustly and cost-effectively on a large-scale. Additionally, the *National Non-Food Crop Centre (NNFCC)* is an international consultancy, based in York, with expertise on the conversion of biomass to bioenergy, biofuels and bio-based products, which can help to support commercialisation activities.

The forthcoming BBSRC *Networks in Industrial Biotechnology and Bioenergy (NIBBs)* should also provide a useful mechanism to facilitate knowledge transfer, leading to commercialisation (see also response to question 4).

A comprehensive list of Government innovation funding opportunities for low-carbon technologies can be found on the gov.uk website. It may be helpful for the Government to develop a similar resource specifically for waste valorisation.

European Initiatives

BIOCHEM is a partnership programme that supports companies across Europe (particularly SMEs) which aims to enter the market in bio-based products in the chemical sector. The seventeen consortium partners from eight European nations include innovation agencies, venture and public funding bodies. The project has developed tools, methodologies and processes that aid market entry by providing market information and access to funding directories. These resources and

The benefits for the UK of this European programme are:

Alignment of research priorities bio-based products in the chemical sector is an area of research strength in the UK, with the Centre of Excellence in Green Chemistry at the University of York, the Centre for Sustainable Chemical Technologies at the University of Bath and the planned Centre of Excellence for Sustainable Chemistry at the University of Nottingham, in collaboration with GlaxoSmithKline. Participation in European programmes such as BIOCHEM can help ensure that the future returns on such research can be maximised.

Access to tailored support for SMEs SMEs encounter many difficulties with respect to start- -stop hat is tailored to a specific market sector.

Exposure for UK SMEs to international finance

COST Action TD120 – Food waste valorisation for sustainable chemicals, materials & fuels (EUBis): A new

Polymers made from new and unique biomass feedstocks may eventually overtake petrochemical-derived plastics in terms of superior properties and functionality.[6]

C. Governance

7. Do Government, the Research Councils and the Technology Strategy Board have a co-ordinated funding strategy for this area? Are effective mechanisms in place for funding cross disciplinary research?

Multidisciplinary Collaboration

Greater multidisciplinary collaboration between scientists across disciplines should be enabled by bespoke funding sources.[7,8] Research to develop new bio-waste technologies requires multidisciplinary teams across academia/industry boundaries. A threat to multidisciplinary research is that research topics at the boundaries of two funding bodies/programmes run the risk of being under-supported by both.

A big challenge for the chemical science community is that some chemists lack awareness of the many research opportunities in biomass conversion nor do they have an understanding of where they can play a role. Educating the next (and current) generation of scientists to embrace a multidisciplinary approach will be vital. There is a role for learned societies, including the *Royal Society of Chemistry*, to raise awareness of the area amongst the chemical science community and in developing the research community networks that will be needed to provide future breakthroughs. Research networks of chemists, chemical engineers and biological scientists will be needed, working together with entrepreneurs, food processors and farm managers where appropriate. For instance, in May 2013 The *Environment, Sustainability and Energy Division (ESED)* of the *Royal Society of Chemistry* brought together a multidisciplinary community through a conference that was jointly run with the *American Chemical Society (ACS) Polymer Division* on the topic of *Sustainable Polymers*. The need for more and better multidisciplinary collaborations is also an acute challenge in the area of drug discovery. The *Royal Society of Chemistry*, in partnership with other learned societies, is spearheading a new initiative under the *Drug Discovery Pathways Group (DDPG)* banner to support and develop industry-academia partnerships in drug discovery. The area of bio-waste valorisation would likely benefit from a similar initiative.

Funding Initiatives

There appear to be several mechanisms in place for funding cross be ross

sources by 2020. Suppliers who supply >450,000 litres of road transport fuel are obligated under the RTFO. A significant proportion of the total biomass feedstock used across the UK to produce renewable transport fuel originates outside the UK (See recent statistics below). There is an opportunity to legislate to increase the amount of local bio-waste utilised for this purpose. From *Renewable Transport Fuel Obligation Stats* (first three quarters of obligation year 15 April 2012 to 14 April 2013):

> Of the 632 million litres meeting sustainability criteria, bioethanol comprised 55% of supply, biodiesel (FAME) 39% and biomethanol and methyl tertiary butyl ether (MTBE) 6%. There were also small volumes of biogas, and pure vegetable oil.
>
> The most widely reported source (by feedstock and country of origin) for biodiesel was used cooking oil from the UK (55 million litres, 22% of biodiesel).
>
> The most widely reported source (by feedstock and country of origin) for bioethanol

Appendix 1: Relevant UK pilot facilities

The *Biorenewable Development Centre (BDC)* opened in York in 2012. Facilities at the BDC are open-access and arranged in modules allowing flexibility in the design of processes to convert pants and bio-wastes into high value products.

In the Midlands, the *Food and Biofuel Innovation Centre (FBIC)*,

Appendix 2: Research opportunities for bio-waste valorisation

Development of pre

Appendix 3: ISI Web of Knowledge publishing data

Search terms used: bio-waste; industrial biotechnology; biowaste; synthetic biology; waste gas; platform chemicals; waste feedstock; biomass; catalysis; biomass catalysis; waste biopolymer

NB: Both volume of articles AND number of citations for published articles under all search terms have increased significantly (globally) between 1993 and 2013 (the time period covered by the analysis). UK refers to only England, Scotland and Wales due to ISI reporting methods.

Keyword: Bio-waste

No of articles identified: 103
Top three countries for articles India (24), Germany (19) and Italy (11)
No of articles from the UK: 6
Publications years: 2 in 2012 and 1 in 2013 (plus one from 2001, 2007 and 2008)
UK Organisations involved: Newcastle University, Sheffield Hallam University, University of Manchester Institute of Science and Technology
Funding agencies: EPSRC

Keyword: Biowaste

No of articles identified: 476
Top three countries for articles Germany (75), Spain (49) and Austria (40)
No of articles from the UK: 18
Publications years: 4 in 2008 and 2 in 2010 and 2012 (plus one from 1998, 2002 -2008)
UK Organisations involved: Imperial, Glasgow Caledonian University, University of Leeds, University of Reading, Bangor University, Cranfield University, Scottish water, University of Birmingham, University of London, University of Oxford, University of Strathclyde, and University of Warwick
Funding agencies most involved: BBSRC, EPSRC, EU, Royal Society, UK DEFRA

Keyword: Waste gas

No of articles identified: 16333
Top three countries for articles USA (2963), China (1629), Japan (1234)
No of articles from the UK: 977
Publications years: 88 in 2010 and 2012, 79 in 2011 and 46 in 2013 (articles date back from 1993)
UK Organisations most involved: University of Leeds, Imperial, University of Sheffield, University of Manchester, Cranfield University, University of Birmingham, University of Southampton, University of Cambridge, Newcastle University, University of Nottingham, UCL, and University of Strathclyde.
Funding agencies most involved: EPSRC, EU, NERC, DEFRA

Keyword: Waste feedstock

No of articles identified: 1990
Top three countries for articles USA (506), China (187), UK (170)
No of articles from the UK: 170
Publications years: 25 in 2012, 20 in 2010, 19 in 2013 and 17 in 2011 (articles date back from 1993)
UK Organisations most involved: University of Leeds, University of Southampton, University of Manchester, Newcastle University, Aston University, University of Cambridge, University of Glamorgan, University of Nottingham, University of York, University of Edinburgh and Imperial.
Funding agencies most involved: EPSRC, EU, BBSRC, DEFRA

Keyword: Industrial biotechnology

Keyword: Biomass and Catalysis

No of articles identified: 16333
Top three countries for articles USA (2963), China (1629), Japan (1234)
No of articles from the UK: 977
Publications years: 88 in 2010 and 2012, 79 in 2011 and 46 in 2013 (articles date back from 1993)
UK Organisations most involved: University of Leeds, University of York, University of Birmingham, University of Liverpool, Newcastle University, University of Nottingham
Funding agencies most involved: EPSRC, Royal Society, BBSRC, EU, DEFRA

Keyword: Waste Biopolymer

No of articles identified: 1990
Top three countries for articles USA (506), China (187), UK (170)
No of articles from the UK: 487
Publications years: 39 in 2012, 37 in 2010, 17 in 2013 and 27 in 2011 (articles date back from 1993)
UK Organisations most involved: University of Bristol, University of Leeds, University of Nottingham, University of Cambridge, Imperial, University of Oxford, University of Birmingham, Cranfield University (All other institutions involved can be found in the spread sheet)
Funding agencies most involved: EPSRC, Royal Society, BBSRC, EU

Appendix 4: Companies with potential links to bioeconomy

The following list of companies was assembled from the *MINT database of UK companies* (using the search terms Biomass, Catalysis, Biopolmer/bio-polymer, biowaste, waste gas, waste feedstock, industrial biotechnology, synthetic biology and platform chemicals