Waste Opportunities: stimulating a bioeconomy

Royal Society of Chemistry Response to the House of Lords Select Committee on Science and Technology Call for Evidence

We welcome the opportunity to respond to this *House of Lords Select Committee on Science and Technology* call for evidence.

The opportunities for bio-waste in stimulating a bioeconomy have been the primary focus of the Royal Society of Chemistry's response to this inquiry. The related but distinct theme of biomass (which would include the associated issues of sustainable land use and competition between food and non-food crops) has been referred to in some instances, but has not been covered in significant detail. A review of UK expertise for exploitation of biomass was carried out in 2009.

Executive Summary

A. Science and technology

Abundant volumes of waste are generated in the UK (almost 300M tonnes each year), containing a huge diversity of functionalised chemical components, which could be exploited for higher-value applications, a process collectively known as *waste valorisation*. Conventional food-waste processing misses the large opportunity to exploit the molecular complexity that exists in bio-waste for value-added products.

Waste is generally dispersed geographically across the UK and the Government should consider introducing tax incentives for companies using local waste as a feedstock. Bio-waste storage and spoilage is a major difficulty to overcome. For the future UK sector, there will likely be a balance between establishment of big facilities and more portable/adaptable technologies that can be integrated into individual plants/facilities. There needs to be a coherent and joined-up approach to the use of biomass, both in the UK and globally, to avoid inflating the price for potential users.

There is a major opportunity for the UK to develop and export world-leading, innovative waste valorisation technologies. Several key areas of technology must be developed, and fundamental bioprocessing science will have to mature, for bio-based renewable chemicals to compete with fossil-fuel based feedstocks. The UK research community should remain internationally connected and there is a significant abundance of opportunities in Europe. The UK has a number of centres that are focusing on sustainability and biomass conversion that should seek to engage with *BRIDGE 2020* in particular.

B. Commercial Exploitation and the Bioeconomy

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. One of the big challenges to commercialisation encouraging food companies and chemical companies to work together to unite feedstocks with new processes. Financial incentives such as tax breaks should be implemented by Government to encourage chemical companies to embrace bio-waste feedstocks and to drive change across the sector.

Strategic coordination of relevant funds distributed through agencies such as the Technology Strategy Board (TSB) and associated Knowledge Transfer Networks (KTNs) and Catapult Centres will be important to support growth in the sector. Advances in fundamental sciences, in particular analytical, separation and purification science will be vital to the development and feasibility of future technologies.

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 crucially important.

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 "waste valorisation", or adding value to the waste stream in an economically viable manner, may be a more appropriate definition for this research area than enabling "high-value products". For example, it is possible to obtain gold (a high-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 reduce the UK's 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 particularly significant.

[1] *Food waste as a valuable resource for the production of chemicals, materials and fuels: Current situation and global perspective*, *Energ. Environ. Sci*. **2013**, *6*, 426
[2] *A Sustainable Global Society: how can materials chemistry help?*, Royal Society of Chemistry, 2011
[3] *Chemistry for Tomorrow's World: a roadmap for the chemical sciences*, Royal Society of Chemistry, 2009

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 (as peat alternatives).

There is an opportunity to exploit the low value agri-pellets that used in large quantities by power stations. It could be possible to obtain chemical value from these pellets before they are burned, as well as obtaining useful products from the ashes following incineration.

There has been increasing interest in exploiting lignocellulosic wastes (e.g. field straw) and energy crops (e.g. *miscanthus*) to produce bioethanol liquid fuel over the last 5 years. There are several biorefining and green chemistry centres seeking to exploit bio-waste, in particular in Norwich, York, Nottingham, Aberystwyth, and the Centre for Process Innovation at Wilton (see *Appendix 1*).

Research opportunities

For bio-based renewable chemicals to compete with fossil-fuel based feedstocks there are several key areas of technology that must be developed; and fundamental bioprocessing science will have to mature. A list of relevant research areas that are needed (and currently being explored) can be found in *Appendix Two*. Research publication data can be found in *Appendix 3*.

2. Where does the waste come from and is there a reliable supply?

Wastes may be classified as avoidable (e.g. caused by human error or behaviour) and unavoidable (e.g. part of process chain activities, such as vegetable trimmings from *Brassica*). The global waste market (municipal, industrial waste management, recycling, waste-to-energy, sustainable packaging) is currently estimated to be worth $1trillion a year, and this is likely to double to $2trillion over the next 7 years. The energy from waste market is currently $7.4 billion and could grow to $81 billion by 2022.

The UK produces nearly 300M tonnes of waste each year from several sources. *Bio*-wastes come from a range of different sources and can be mapped onto the agri-food chain. These include field wastes, storage wastes, processing wastes, retail wastes and consumer wastes. The *World Energy Council* gives a useful summary of the biomass available in the UK.

There is a reliable supply of waste from agri-food chain activities. However:

- waste is generally dispersed geographically across the UK. This means that it is expensive to collect and consolidate for valorisation.
- a co-product that has left the food processing line and entered the waste stream is no longer food grade and thus loses potential value
- biowastes often undergo microbiological spoilage and degradation thus devaluing them further
- wastes are often heterogeneous (i.e. come as a mixture of solid and liquids) at different length scales which means they are expensive to process.

For a comprehensive review of quantities of food waste along global supply chains, please see the recent 2013 review article in *Energy & Environmental Science*.[1]

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-waste needs to be concentrated in a high volume (i.e. be concentrated together into a high quantity), be high value and to be available within one locality in order to be economically and environmentally viable as a feedstock.

The Government should consider introducing tax incentives for companies using local waste as a feedstock. It makes both economic and environmental sense to use as much waste (originating in the UK) as possible to reduce the reliance on imported biomass and to enable processing to take place close to waste source. The UK's *Renewable Transport Fuel Obligation Stats* between April 2012 and 14 April 2013 showed, for instance, that the most widely reported source of renewable transport fuel (by feedstock and country of origin) for bioethanol was corn from the USA (171 million litres, 49% of bioethanol) and that only 18% of sustainable renewable fuel was sourced from UK feedstocks. Field wastes (e.g. straw) are reliably produced through cereal production. However they can be transported only 30-40 miles after which the cost of transport (economic and environmental) outweighs the benefits of exploitation. Setting waste usage targets at a local Government level may help to encourage this and may offer the opportunity to exploit domestic bio-waste.

In developed countries, including the UK, there are well established food supply chains which inherently localise waste in high volumes in a way that can be exploited for valorisation. This principally occurs because of large food processing plants and gives the UK a competitive advantage in valorising food waste over developing countries. In India, for example, where there are not well-established food supply chains (there are no supermarkets for instance), the volumes of waste are more dispersed. This means that bio-waste streams are not feasibly available for biomass conversion, even though the absolute volumes of waste produced in India are likely to be higher than in the UK.[1]

Processing and Storage

A major difficulty associated with bio-waste (compared to fossil fuel feedstocks) is that it must be dried before chipping (for cellulosic waste), storage or transport and must be kept dry to prevent spoilage. There are large energy and storage costs associated with these processes. Furthermore, stored biomass can expand and emit gases, due to decomposition, which can be explosive. Stored biomass is notorious for producing smells, which are very difficult to contain using containment facilities, and this is a very difficult problem to overcome. This issue is made worse by local populations becoming sensitised to the odours, even at low levels of concentration.

One of the most utilised processes to obtain value-added products from food waste in the UK is anaerobic digestion (AD). There are around 16M tonnes of business and household waste suitable for AD in the UK, but to make this available for use there is a need for developers need to work more closely with local authorities to promote segregation of different types of wastes, in particular household waste. The UK currently has around 50 AD plants designed to treat food waste with a combined capacity of 1.8M tonnes, and there are another dozen in construction with a capacity to treat a further 0.68M tonnes of food waste. This suggests that there is a capacity to treat 15% of UK business and household waste in this way. AD can complement composting systems by treating waste that can't be processed through windrow composting (the production of compost by piling organic matter or biodegradable waste, such as animal manure and crop residues, in long rows, e.g. cooked kitchen waste and animal by-products).

Maximising Potential

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. There are a number of culture collections, for example the National Collection of Yeast Cultures, containing a large and diverse quantity of genetic information that could be explored for waste valorisation purposes. Industrial processes exist to convert biomass into polymer components microorganisms. Sometimes, the efficient separation of products produced from fermentation mixtures is a challenge, requiring energy-intensive and expensive purification steps, in addition to large water requirements. These can undermine the economic viability of the process. Technological advances, including new catalysts, have the potential to deliver improved processes which use less energy and water than conventional procedures from petrochemicals (see *Appendix Two*).

Future Viability

Adequate information on the environmental and economic viability of different feedstocks is currently unavailable due to the inherent complexity of the supply chains and associated systems. Government should encourage and support a sustained research and development effort, accompanied by trials, which will be required to make appropriate assessments. There is a key question around how sustainable and environmentally benign the current biomass-based processes and catalysts are, and whether more needs to be done ensure they are meeting sustainability standards. The Royal Society of Chemistry welcomed the Government's recent announcement that £90M will be invested in Centres for Agricultural Innovation, as part of the UK Agri-Tech strategy. It has already been announced that the first of these centres will be a *Centre for Agricultural Informatics and Metrics of Sustainability*. Considering the inherent links between the bio-based economy and agriculture, this is a welcome step and has the potential to contribute to the development of clearly defined standards in relation to bio-based products.

For the future UK sector, there will likely be a balance between establishment of big facilities that support biomass conversion within a geographical area and smaller, more portable/adaptable technologies that can be integrated into individual plants/facilities.

There needs to be a coherent and joined-up approach to the use of biomass, both in the UK and globally, to avoid inflating the price for potential users. The price of straw has risen, for instance, as its demand as an energy source has increased, and this in turn has reduced the commercial attractiveness and viability of exploiting straw for biofuel production.[4]

How strong is the UK's research base in this area relative to the rest of the world?

The UK research base has some focal points of world class activity in deriving value-added products from waste streams. *Appendix Three* identifies a number of academic research groups, with research tending to be clustered in certain institutions. Some examples include the universities of Leeds, York, Bristol, Nottingham, Cambridge, Bath, Southampton and institutions around Norwich, to name only a few.

[4] *Environmental sustainability of bioethanol production from wheat straw in the UK*, Renewable and Sustainable Energy Reviews. 28, 2013, 715

There is significant expertise and a technology base in the UK already (both within universities and technology-provider companies). Support mechanisms are available for businesses to take advantage of this, for instance the imminent launch of *Networks in Industrial Biotechnology and Bioenergy (NIBBs)* by the BBSRC and the 2014 *IB Catalyst Fund* in conjunction with the TSB, should provide a real focus for companies to exploit these multi-disciplinary networks for expertise.

The perception of some members of the UK research community is that the field would benefit from additional process engineering research. Initiatives that bring engineers and chemical engineers together with other scientists, in a multidisciplinary way, would be especially welcomed by the research community.

Opportunities for UK Researchers in Europe

Outside the UK, there is an abundance of opportunities within Europe in bio-waste exploitation, and sustainable development is an overarching objective within *Horizon 2020*. Waste valorisation research could significantly benefit from the €70 billion of available funding within *Horizon 2020* and there are specific European initiatives in which the UK community must maximise its involvement. Key initiatives include *Sustainable Processes for Industry through Resource and Energy Efficiency (SPIRE 2030)*, which is a European public-private partnership (PPP) dedicated to innovation in resource and energy efficiency in the process industries, and *Biobased and Renewable Industries for Development and Growth in Europe (BRIDGE 2020)*, which aims to optimise the use of current bio-based feedstocks, as well as to develop new bio-based feedstock chains.

BRIDGE 2020 is the more relevant to the development of bio-waste utilising technologies. The projects here will be developed around 5 specific value chains, including one that focuses on bio-waste. The opportunity to join and work as part of this consortium represents an important route for UK researchers and industrialists to collaborate with other researchers/companies to become part of value chains across Europe.

The UK has a number of centres that are focusing on sustainability and biomass conversion that should seek to engage with *BRIDGE 2020*.

2014 is the *European Year of Food Waste*, providing an opportunity for the UK community to promote and raise awareness of the UK sector.

Beyond Europe

There is a significant opportunity for the UK to develop and export technologies to developing countries, and for this reason the UK should be internationally aware and connected. Nations such as Brazil and Vietnam are establishing a presence in bio-waste valorisation. The Brazilian Government's *Science Without Borders* programme is enabling thousands of young Brazilians to interact with the international scientific community and the BBSRC has initiated a UK-Vietnam partnership programme to explore research towards valorising food supply chain waste (such as rice straw) in Vietnam. There also appears to be a focus of waste valorisation in India and possibly in China and Chile. See *Appendix Three* for an indication of countries currently undertaking research in this area.

B. Commercial exploitation and the bioeconomy

4. How large is the current market and what types of products generated from bio-waste and waste gas are currently commercially available? How does this compare to elsewhere in the world?

An accurate assessment of market size requires a breakdown of different wastes and different markets. Realistically, it is best to focus on waste streams produced from large, centralised 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-plastics, will be produced from biological rather than petro-chemical feedstocks. The *Lead Market Initiative for Bio-based Products* has provided a useful analysis of the European markets for bio-based products and already had some impact in stimulating demand for innovative new products, through its *Vision for Sustainable Growth*.

Are there appropriate mechanisms in place to facilitate commercialisation?

Perspectives from researchers working in this field suggest commercialisation mechanisms could be strengthened to encourage further growth in the sector. Strategic coordination of relevant funds distributed through agencies such as the Technology Strategy Board (TSB) and associated Knowledge Transfer Networks (KTNs) and Catapult Centres will be important to support growth in the sector.

There is a strong and highly experienced skills base in the UK's chemistry-using industries which are well-placed to commercialise new technologies. The required skills base for these industries needs to be nurtured through a clear strategy for higher education. It should be noted that there will be an inherent delay in realising the benefits of changes to higher education while courses are established and graduates emerge from the system. There is also a need to establish clearer career pathways for individuals wishing to enter the emerging commercial sector.

[5] *Food waste as a valuable resource for the production of chemicals, materials and fuels: Current situation and global perspective*, *Energ. Environ. Sci*. **2013**, *6*, 426

Significant expertise exists within the UK's higher education sector. However, the perception of some members of the research community is that there can be a focus on research towards low volume, high value products which may not have as much commercial potential as high volume, low value applications. They suggest that further incentives to encourage HEIs to engage in applied waste valorisation research through TSB initiatives would be helpful; however this should not come at the expense of fundamental research.

Commercialisation Challenges

Barriers that have an inhibiting effect on the growth of the UK sector include:

- risks associate with investing in low-value, high volume novel processes which compete with well-established commodity markets.
- A general lack of knowledge, familiarity and fundamental understanding of the potential of bio-based feedstocks to produce chemicals, materials and fuels within chemistry-using sectors and amongst entrepreneurs.
- Limited facility access and funding for development and scale-up opportunities, including for upstream pre-treatment of biomass and downstream operations, especially for SMEs and entrepreneurs.
- Lack of connectivity, communication and collaboration between waste-providing upstream and waste-using downstream supply chains in the UK, in particular between the food sector (upstream) and the chemicals sector (downstream).
- Limited permeation of multidisciplinary skill-sets across relevant sectors to facilitate collaboration and knowledge sharing.
- The need for a clear strategy within Higher Education to nurture and incentivise the multidisciplinary skills-base that will be required for sector growth.
- A shortage of research efforts in Higher Education Institutions and Research Institutes specifically focused on low-value, high volume waste valorisation applications.

There is a tendency for chemical companies to work on more traditional compounds or products that are already in commercial use. One of the big challenges to commercialisation is encouraging food companies (that generate feedstock waste) and chemical companies (that could potentially use this feedstock) to work together to unite feedstocks with new processes.

Financial incentives such as tax breaks should be implemented by Government to encourage chemical companies to embrace bio-waste feedstocks and to drive change across the sector. Such incentives would help to mitigate the associated financial risk of developing new processes, which in many instances will likely involve designing and constructing a whole new plant and set of processes to utilise a new bio-based feedstock. This operation is disruptive, expensive and slow, especially for large companies.

Chemical companies will need to take an innovative approach to process design in order to use new waste feedstocks from food. In this respect, small companies may be better placed to explore new, innovative processes. Initiatives/funding to support food companies and chemical companies (of all sizes) to work together on exploiting bio-waste feedstocks would be welcome. Support for SMEs could be encouraged through specific initiatives within existing Government schemes, including those provided by the TSB and KTNs.

The challenges and recommendations identified in the recent House of Commons Science and Technology Select Committee inquiry into the *Bridging the 'Valley of Death'* will likely be of relevance to encouraging commercialisation and knowledge transfer in the area of bio-waste exploitation.

UK Initiatives

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 others, provided in one central location, form a 'BIOCHEM toolbox'.

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-up funding and access to markets. Programmes like BIOCHEM provide a 'one-stop shop' that can provide SMEs with a wide range of assistance that is tailored to a specific market sector.
- Exposure for UK SMEs to international finance – As the programme is run at a European level across a number of partners, a wider group of potential investors in UK SMEs can be identified and approached for venture capital.
- Many of the projects have led to SMEs successfully finding investors and partners for development. One UK exemplar is *Starbon Technologies* which emerged from the *Green Chemistry Centre of Excellence* at the University of York.

ERA-NET Plus BESTF: The UK has pledged up to £10M (€12.5M) to a scheme to develop innovative bioenergy projects, in partnership with seven other EU countries. The ERA-NET Plus BESTF scheme, worth around €47million in public money, will stimulate up to €100m of bioenergy innovation projects in the UK, Finland, Sweden, Germany, Spain, Denmark, Switzerland and Portugal.

COST Action TD120 – Food waste valorisation for sustainable chemicals, materials & fuels (EUBis): A new *European Cooperation in Science and Technology (COST)* Action (TD1203) has recently launched, entitled *Food waste valorisation for sustainable chemicals, materials & fuels (EUBis)*. The overall aim of EUBis is to bring about a critical mass of researchers and stakeholders to harness the potential of food supply chain waste as an alternative carbon source to produce commercially viable chemical commodities. Over 100 European labs are already involved and there have been expressions of interest from scientists in both Hong Kong and Brazil. EUBis represents a significant opportunity to develop the UK sector at a European level.

Bio Base NWE: A new scheme provided by Bio Base NWE has been launched to help small and medium enterprises in North West Europe assess the feasibility of taking a bio-based idea or technology to industrial production. SMEs (including those in the UK) can apply for 'Innovation Coupons', worth up to €10,000 (£8,400) each, which can be used to access the state-of-the-art technology and expertise of the Bio Base Europe Pilot Plant in Ghent, Belgium. The scheme launched in April 2013 and is a €6.2m project funded under the INTERREG IVB NWE framework programme to support the development of the bio-based economy in North West Europe.

BRIDGE 2020 will also be an important future mechanism for the UK to work as part of a pan-European effort to improve commercialisation of technology in this area (see response to Question 4).

5. Which types of products will be on the market in five, ten and twenty years from now and which factors will influence this?

The predominating factor that will influence the demand of new products for the foreseeable future will be the relative cost of fossil fuel feedstocks. The increase in oil prices in 2007 stimulated the interest in alternative biofuels. Because of this, the drop in price due to the recession, and the finding of other energy sources such as shale gas, has reduced this imperative.

Nevertheless it is envisaged that bioethanol and some platform chemicals will be available in the near future together with various low volume extracts from waste streams with commercially-attractive properties (such as prebiotics).

Other products likely to emerge are new biologically-derived polymers can be designed that are biodegradable, with thermal and mechanical performance that is competitive with conventional petrochemical-based plastics. In the first development stages, biologically-derived polymers will likely complement petrochemical-based plastics rather than directly compete with them. In the longer-term, however, biologically-derived plastics could be utilised to produce higher value products where a cost premium is justified on the basis of additional functionality. Scientific advances in current technologies are necessary to achieve replacement of petrochemical products on a broad scale (see response to Question 1).

Advances in fundamental sciences, in particular analytical, separation and purification science will be vital to the development and feasibility of future technologies. For instance, the detection of low concentration, high value products within complex waste streams would have been extremely difficult using technology available only 10 years ago. Many novel techniques originate in research laboratories and are scaled up for commercial applications. Similar fundamental advances will be crucial to the development of future waste valorisation technologies.

6. What is the potential contribution of this technology to a bioeconomy?

The use of biomass as a feedstock offers the opportunity to exploit the molecular complexity that exists in nature and which could greatly enhance the practical uses of chemicals available from biomass. With appropriate science and manufacturing developments (see response to question 1), the manufacture of these products could be more sustainable than their synthesis from oil.

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-disciplinary research in bio-waste conversion. However, the cessation of *DEFRA LINK* funding has been a significant loss. At present there appears to be sufficient funding for (and existing strength in) fundamental research in this area; however increased support for research at the applied/commercialisation end is needed. TSB funding exists, though the industry partners (a requisite of TSB funding) often have a much shorter-term interest than that required to develop exploitation technologies for wastes; and academic partners often fail to understand the timescale needs of industry partners. This may be addressed to some degree by the forthcoming BBSRC *Networks in Industrial Biotechnology and Bioenergy (NIBBs)*, and the associated *IB Catalyst* funding calls.

The *Integrated Biorefining Research and Technology Club (IBTI Club)* is a £6 million, five year initiative aimed at developing biological processes and feedstocks to reduce our current dependence on fossil fuels as a source of chemicals, materials and fuel. This initiative is a partnership between the BBSRC, EPSRC, industry and the Biosciences KTN. Similarly, the *BBSRC*

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[6] *A Sustainable Global Society: how can materials chemistry help?*, Royal Society of Chemistry, 2011 (http://www.rsc.org/ScienceAndTechnology/roadmap/sustainable_global_society/CS3_download.asp)
[7] *Chemistry for Better Health*, Royal Society of Chemistry, 2012 (http://www.rsc.org/scienceandtechnology/roadmap/chemistry-for-better-health-white-paper-cs3.asp)
[8] *Face to Face: the UK chemistry biology interface*, Royal Society of Chemistry, 2008 (http://www.rsc.org/ScienceAndTechnology/Policy/Documents/facetoface.asp)

Crop Improvement Research Club (CIRC) may help to develop waste streams that are more suitable for valorisation. These 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 (see response to question 4), but the UK is currently woefully under-represented in these PPPs. The TSB, along with appropriate KTNs and learned societies (including the *Royal Society of Chemistry*), has a major role to promote membership of the PPPs to UK industry.

On 1 August 2013 the Department for Transport announced £25 million of capital funding to enable the construction of demonstration-scale waste to fuel and other advanced biofuel plants in the UK. It is intended that this investment will underpin significant private sector investment in one or more demonstration-scale advanced biofuel plants in order to drive the development of the UK's biofuel industry, including fuels from bio-wastes. The strategy behind the establishment of new facilities should take into account the capacity that already exists to conduct demonstration-scale studies into bio-waste valorisation (see *Appendix 1*)

See also commercialisation initiatives identified in response to question 6.

8. Does Government have a joined up approach to policy and regulation, which effectively supports the growth of this area?

Policy

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.

The UK has a target of 10% for the proportion of transport energy to be obtained from renewables by 2020 since the EU passed legislation to cap the use of food-based biofuels, meaning that the UK will need to diversify the means by which it meets the 10% target. Advanced biofuels, made from wastes and residues, could make up the shortfall but the scale of development is unlikely to make a significant impact on the 2020 targets without strong policy support.

Below is an overview of UK and European policy affecting the valorisation of bio-waste in the UK, and accompanying recommendations:

- **The European Community (EC) Directive 1999/31/EC on the landfill of waste ("Landfill Directive"):** The *Landfill Directive* requires the UK to reduce biodegradable municipal waste going to landfill to 35% of baseline (1995) levels by 2016. This will limit the quantities of biodegradable waste sent to landfill, together with the landfill tax set at £56 per tonne (April 2011) and rising. The percentage of waste that we send to landfill is dropping. Growth in sectors seeking to make energy and value-added products from bio-waste will help the UK to meet this target.
- **Renewable Energy Directive:** Energy from waste can contribute towards the target set by the *Renewable Energy Directive* – this has set a target of 15% for energy in the UK that should be derived from renewable sources by 2020. The *UK Renewables Obligation Order* encourages the use of renewables for power production, by ensuring energy suppliers provide a set amount of their electricity from eligible renewable sources. This can include the advanced conversion of waste and anaerobic digestion for fuels; and energy from waste by incineration with combined heat and power. The Government could consider setting additional renewable energy targets that extend beyond 2020, to provide a greater degree of stability for investors.
- **Renewable Transport Fuel Obligation:** The *Renewable Transport Fuel Obligation* stipulates that the UK must obtain 10% of its energy used in transport from renewable

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 was corn from the United States of America (171 million litres, 49% of bioethanol).
  - 18% of sustainable renewable fuel was sourced from UK feedstocks.

- **DECC Sustainability Criteria:** Government have introduced financial support under the *DECC Sustainability Criteria* for companies that can demonstrate sustainability in their use of biomass. This will provide a period of stability for investors up until 2027.

- **UK Bioenergy strategy:** The *UK Bioenergy strategy* published in April 2012 jointly by DECC, Defra and the Department for Transport makes some important points relevant to the bio-economy. This document states that sustainably-sourced bioenergy may contribute 8-11% of the UK's total primary energy demand by 2020 and that this figure may rise to 12% by 2050 (broadly within a range of 8% to 21%). It states that international supplies, particularly from North America, will be a vital contribution to this. However, legislation should encourage the sector to use as much UK waste as possible to reduce the reliance on imported biomass (see response to question 3). The strategy states that 'uncertainty' is a feature of this sector and recognises that the UK Government needs to manage this uncertainty carefully in its engagement with businesses and others.

- **Government Review of Waste Policy in England 2011:** The *Government Review of Waste Policy in England 2011*, carried out by Defra, provides a commitment to managing waste in line with the waste hierarchy (see response to question 3). It states that "the waste and resource management industry contributes a significant amount to the UK economy and employs over 100,000 people. It is an industry in transition and one whose continuing economic growth we want to support. For businesses of all shapes and sizes there are major savings for the bottom line from using resources more efficiently."

  Much of the Waste Policy review focuses on waste management practices, rather than treating waste as a resource (valorisation). Existing policy dealing with waste recovery are largely focused on energy generation, rather than creation of higher-value products. Similarly, previous Government initiatives, for instance the *Biomass Energy Centre*, have largely focussed on production of energy. The reduction of food waste quantities across Britain could go hand-in-hand with valorisation. There are significant opportunities for the UK to convert our waste streams into economic value through our chemicals and IB industries, while simultaneously helping to meeting renewable energy and climate change targets.

- **Energy from Waste and Incineration:** The 2011 parliamentary briefing paper *Energy from Waste and Incineration*, considers waste incineration as a means of generating energy. The incineration route does not maximise the numerous valorisation benefits that could be realised from waste. Waste incineration has the added disadvantage that it is suffers from a highly negative public perception, as was demonstrated with the recent controversy around the establishment of a waste incinerator in Kings Lynn, Norfolk.

  The Government also has an independent *Anaerobic digestion strategy and action plan*, which also appears to focus largely on energy recovery exclusively, and does not include chemicals and materials. Anaerobic Digestion, however, does offer a suitable starting point towards valorising waste for added-value products, rather than simply incinerating for energy recovery.

Regulation

Since much of the relevant regulation affecting businesses is shaped at the EU level, participation in discussions at European level is crucially important. Within the *BRIDGE 2020* there is a specific focus within one of the supporting projects examining 'Standards and Regulations' which will involve working with the *Comité Européen de Normalisation* (CEN - the European Committee for Standardisation). Participation in *BRIDGE* represents an additional way that UK business can influence the discussion and formation of standards and regulations in the bio-based industries sector.

Wastes that have the potential to be exploited further for value-added products may be called "co-products". Industry may prefer this terminology because it avoids the perception that resources are being wasted. Furthermore, there is a legal definition of "waste" which can cause complications for the onward use of materials.

For an overview of the influence of food regulations on food supply chain waste valorisation and society's behaviour towards food supply chain waste, please see the recent 2013 review article in *Energy & Environmental Science*.

The *Novel Foods (EC 258/97)* legislation requires extensive investment in testing and evaluating new ingredients, and it is possible that this curtails investment in research aimed at exploiting food chain wastes and co-products for use as sources of food ingredients.

Like all new materials, the regulation of new bio-based materials will need to consider the break-down/end-of-life materials that result during their degradation, and the any resulting impact on human health and the environment. In this context it will be important to establish appropriate standards for bio-based products through *CEN/TC 411 Bio-based products*.

The control of levels of micro-contaminants in new products will also need to be carefully considered, together with the possible releases of bioactive materials and odours into the atmosphere. The mechanical food waste facilities that many local authorities have installed to replace incinerator facilities need to be appropriately regulated to limit the spread of virus and bacterial material.

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)*, at The University of Nottingham, conducts research on brewing, food processing and bioenergy production. Brewers *SABMiller* are partners in the project and have developed a 1000 litre pilot scale brewery within the centre.

Norwich Research Park (NRP) is home to the *Institute of Food Research Biorefinery Centre*, which contains a steam explosion pilot plant. The pilot plant can be used to convert lignocellulosic biomass into next generation biofuels and chemicals using a thermal/hydrolysis process which operates at up to 230°C.

The *Beacon Biorefining Centre of Excellence* in Wales is a focal point for IB research. Beacon is a collaboration between Aberystwyth, Bangor and Swansea Universities. Aberystwyth boasts a plug and play, multi-feedstock pilot processing plant. Bangor hosts a pressurised refining and pilot scale facility coupled with supercritical fluid and chemical/analytical support.

The *Centre for Process Innovation (CPI)* with centres at Sedgefield and Wilton (Cleveland) helps companies prove and scale up processes to manufacture to develop sutainable processes for the future. It is one of the Governments Catapult Centres.

Appendix 2: Research opportunities for bio-waste valorisation

- Development of pre-treatment methods for biomass component separation
- Development of pyrolysis and gasification techniques that increase the density of biomass
- Microbial genomics to improve the micro-organisms that break-down and convert biomass
- New technologies that exploit biomethane from waste.
- Development of novel separation technologies, such as membranes and sorbent extraction of valuable components from biological materials
- Advances in fermentation science to deliver a greater variety and yield of products.
- Development and redesign of plant-based feedstocks to improve co-product composition and value
- Processes that allow the retention of inherent nanostructures within biomass, to deliver more highly functionalised compounds.
- New synthetic methods to adapt the oxygen-rich feedstocks that tend to arise from biomass
- Design of enzymes and microorganisms tolerant to oxygen and inhibitors
- Catalysts that can effectively utilise chemicals from biomass will be required as alternatives to traditional processes that use petroleum feedstocks, including those for upgrading pyrolysis oil.
- it will be possible to design families of catalysts for new bio-based feedstocks that function effectively in water, with good levels of efficiency, activity and selectivity.
- design of novel catalysts and biocatalysts for breaking down lignin into aromatic substrates
- design of new, high-efficiency, highly selective catalysts for polymer production from biological feedstocks.
- Design of more active and selective catalytic enzymatic or chemical methods to separate and utilise entire biomass-derived materials completely and efficiently
- Development and optimisation of new methods will be required to enable the selective separation and conversion of recalcitrant lignocellulosic (woody) and other feedstocks into commodity chemicals, polymers, and fuels.
- Development of new copolymers, modified biopolymers, (nano)composites and blends for new materials
- Following the extraction of high-value components from waste material, the bulk of the material still remains and needs to be disposed of. Suitable technologies for the treatment of this material need to be investigated. Examples can be found in recent publications.[9,10]
- Robust and transparent methods for assessing the life-cycle impact of renewables, and comparing alternative routes, are needed. These will enable companies to assess potential energy and greenhouse gas savings and will provide economic incentives to adopt new bio-based technologies.[3]
- The environmental impact of burning fuels that are grown on contaminated land is an emerging issue in some parts of the world. There is therefore need to understand the longer term environmental impacts from traditional incineration routes of biomass, including release of pollutants to the atmosphere that may have originated in contaminated land upon which the biomass was cultivated.

[9] *Handbook of waste management and co-product recovery in food processing (Volumes I and II)*, Woodhead Publishing, 2007 and 2009
[10] *Total Food: Sustainability of the Agri-Food Chain*, Royal Society of Chemistry, 2010

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

- No of articles identified: 1511
- Top three countries for articles – USA (307), Germany (176), UK (106)
- No of articles from the UK: 106
- Publications years: 15 in 2011, 9 in 2012, 4 in 2013 (articles date back from 1993)
- UK Organisations most involved: University of Manchester, Newcastle University, UCL, University of Sussex, Plymouth Marine LAB, University of Abertay Dundee and University of Nottingham
- Funding agencies most involved: EU, BBSRC, DEFRA

Keyword: Synthetic Biology

- No of articles identified: 4550
- Top three countries for articles – USA (2088), UK (453), Germany (406)
- No of articles from the UK: 453
- Publications years: 82 in 2012, 66 in 2011, 58 in 2010 and 41 in 2013 (articles date back from 1993)
- UK Organisations most involved: University of Bristol, Imperial, University of Cambridge, University of Manchester, University of Edinburgh, University of Oxford, UCL, University of Sheffield, University of Glasgow and University of Nottingham.
- Funding agencies most involved: EPSRC, EU, BBSRC, Wellcome Trust, Royal Society and MRC

Keyword: Platform Chemicals

- No of articles identified: 5949
- Top three countries for articles – USA (2419), China (623), Germany (503)
- No of articles from the UK: 422
- Publications years: 55 in 2011, 52 in 2012 and 51 in 2013(articles date back from 1993)
- UK Organisations most involved: University of Cambridge, University of Manchester, Imperial, UCL, University of Oxford, University of Edinburgh, University of York, University of Nottingham, University of Strathclyde, University of Leeds, University of Leicester, University of Southampton and University of Warwick.
- Funding agencies most involved: EPSRC, EU, BBSRC, Wellcome Trust and Royal Society

Keyword: Biomass

- No of articles identified: 140550
- Top three countries for articles – USA (37861), China (11832) Germany (9346)
- No of articles from the UK: 9154
- Publications years: 813 in 2012,763 in 2011, 670 in 2010 and 497 in 2013 (articles published since 1993)
- UK Organisations most involved: Imperial, University of Leeds, University of Aberdeen, University of Sheffield University of Edinburgh, Plymouth Marine lab, University of Southampton, University of Cambridge, University of Oxford, University of York
- Funding agencies most involved: NERC, EU, EPSRC, BBSRC, Royal Society

Keyword: Catalysis

- No of articles identified: 113390
- Top three countries for articles – USA (29698) China (14015) Germany (12045)
- No of articles from the UK: 8194
- Publications years: 510 in 2012,562 in 2011, 520 in 2010 and 291 in 2013 (articles published since 1993)
- UK Organisations most involved: University of Cambridge, University of Oxford, University of Manchester, Imperial, University of St Andrews, University of York, University of Liverpool, University of Bristol, University of Cardiff
- Funding agencies most involved: EPSRC, Royal Society, Wellcome Trust, BBSRC

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) and through consultation with key experts:

ADVANCED PLASMA POWER	INEOS BIO
AECOM	Infinis
AIR PRODUCTS GROUP LIMITED	Jacobs
ALDA CAPITAL LIMITED	JOHNSON MATTHEY (CM) LIMITED
Alkane	Kemble Farms
Argent energy	LONZA BIOLOGICS PLC
Biogen (UK)	MERIT HOLDINGS LIMITED
BIOSSENCE (EAST LONDON) LIMITED	MOREDUN SCIENTIFIC LIMITED
Black & Veatch	MVV ENVIRONMENT RIDHAM LIMITED
BRITE PARTNERSHIP (NORTH EAST) LIMITED	NEW BRUNSWICK SCIENTIFIC (UK) LIMITED
CARRON ENERGY LIMITED	NEWRY BIOMASS LIMITED
CLYDE BLOWERS CAPITAL GP III LIMITED	OXARA ENERGY GROUP LIMITED
CYMTOX LIMITED	PORT OF LIVERPOOL WIND FARM LIMITED
DONG ENERGY LONDON ARRAY LIMITED	PUROLITE LTD
E.ON CLIMATE & RENEWABLES UK BIOMASS LIMITED	ROSE ENERGY LIMITED
E.ON CLIMATE & RENEWABLES UK HUMBER WIND LIMITED	RWE NPOWER RENEWABLES LIMITED
ECO2 LINCS LIMITED	SITA UK
ECONOVATE LIMITED	SLOUGH HEAT & POWER LIMITED
Ener-g	Sustainable energy Limited
EPR EYE LIMITED	TAMAR ENERGY
EPR THETFORD LIMITED	TMO renewables
ESB ASSET DEVELOPMENT UK LIMITED	TUNDRA WOOD HEATING SYSTEMS LTD
FLEETSOLVE LIMITED	USKMOUTH POWER COMPANY LIMITED
GLOBAL GREEN POWER LIMITED	VEOLIA ENVIRONNEMENT
GOOD ENERGY LIMITED	VIRIDIS ENERGY (NORGEN) LIMITED
GREEN CHEMICALS PLC	VIRIDOR
GREENKO GROUP PLC	WASTE2TRICITY
HELIUS ENERGY PLC	WESTERN BIO-ENERGY LTD
HIDEN ANALYTICAL LIMITED	WESTINGHOUSE PLASMA CORP