Final report

Optimising the value of digestate and digestion systems

Identification and evaluation of technologies with the potential to valorise feedstock, the digestion process or digestate

Project code: OIN007-001
Research date: October 2014
Date: May 2015
WRAP’s vision is a world in which resources are used sustainably.

Our mission is to accelerate the move to a sustainable resource-efficient economy through re-inventing how we design, produce and sell products; re-thinking how we use and consume products; and re-defining what is possible through recycling and re-use.

Find out more at www.wrap.org.uk

Written by: Dr Nigel Horan, Matthew Smyth, Ian Cessford

Front cover photography: AD plant, courtesy of WRAP

While we have tried to make sure this report is accurate, we cannot accept responsibility or be held legally responsible for any loss or damage arising out of or in connection with this information being inaccurate, incomplete or misleading. This material is copyrighted. You can copy it free of charge as long as the material is accurate and not used in a misleading context. You must identify the source of the material and acknowledge our copyright. You must not use material to endorse or suggest we have endorsed a commercial product or service. For more details please see our terms and conditions on our website at www.wrap.org.uk
Executive summary

- The amount of organic waste treated by anaerobic digestion has doubled since 2009 with around 11 million wet tonnes treated annually. However there are a number of threats to the continued expansion of this technology, with shrinking gate fees for raw material, increased costs for digestate recycling and potential uncertainty as to the long term sustainability of the land recycling route.

- This project, jointly funded by WRAP and Zero Waste Scotland, seeks to explore alternatives to land recycling which can add value to the whole digestion process with the emphasis on digestate. The outputs from the investigation will inform future funding plans by both WRAP and Zero Waste Scotland for potential investment in the UK organic waste sector.

- An evaluation of the range and extent of technologies available was undertaken via a Rapid Evidence Assessment (REA) with a database that was populated using a range of techniques which included traditional web-based literature searching; face-to-face interviews via exhibition attendance, phone calling, and a specialised search vehicle known as Iveridis. A total of eighteen alternative technologies were identified through these routes that showed potential for adding value to the digestion process or reducing digestate volume.

- A short-list of six technologies was prepared from these eighteen by comparison of their key attributes against a list of research questions posed by WRAP. These research questions covered: i) the technology readiness level of the option; ii) any barriers to its commercialisation; iii) the likely costs to overcome these barriers and thus take to the marketplace; iv) the market impact; v) the adaptability across a range of plant sizes and feed types, and; vi) the commercial value of the technology.

- The six technologies short-listed were: Hydrothermal Carbonisation; Extractive Phosphorus Recovery; Neo Energy; Waste Biorefinery Platform; Carboxylate Platform and Bioplastic Synthesis. A selection matrix was drawn up in Excel format to rank each of these technologies against seven WRAP and Zero Waste Scotland attributes. The attributes were weighted and fully adjustable by the end-user, whereas the rankings were fixed and determined by the technical experts on the project delivery team. This permitted a full sensitivity analysis to be undertaken for each of the attributes by recognising the extent of information, availability of primary/secondary data and validity of evidence. This ensured a robust and transparent selection process to determine the most commercially viable technology options suitable for future funding.

- After assessing the potential of the six technologies there doesn’t appear to be one which is market ready or could be rapidly deployed in the immediate future. However, some of the technologies identified do show significant potential for development in the UK. As such WRAP will undertake a second phase of the project. Its aim being to answer key questions such as their potential to be scaled up while bringing the technologies closer to market.
Contents

1.0 Introduction and background .................................................... 1

2.0 Précis of the method used................................................................. 2
  2.1 Methodology ............................................................................. 2
    2.1.1 Step 1: Scoping of Research Themes .................................. 3
    2.1.2 Step 2 – Development of Coding Strategy, Cloud-based Platform and Database ................................................................. 4
    2.1.3 Step 3 - Rapid Document Identification (Horizon Scan) .......... 4
    2.1.4 Step 4-5 – Gap Analysis and Contact Strategy ..................... 4
    2.1.5 Step 6 - Interim Report and Focusing of Further Research ....... 4
    2.1.6 Step 7 - Detailed Evidence Review and Synthesis ............... 4

3.0 Evaluation of process options .......................................................... 4
  3.1 The options found, their applications and research trends ............... 4
  3.2 The options selected for further evaluation ................................... 9

4.0 Discussion ...................................................................................... 10
  4.1 Production of novel products .................................................... 10
  4.2 Recovery of phosphorus .......................................................... 11
  4.3 Hydrothermal carbonisation ..................................................... 11
  4.4 Waste Biorefinery Platform ....................................................... 12

5.0 Conclusion ..................................................................................... 13

6.0 References ..................................................................................... 14
Glossary of abbreviations

AD  Anaerobic Digestion
BMP  Biochemical Methane Potential
CHP  Combined Heat and Power
Defra Department for Environment, Food and Rural Affairs
EU  European Union
FiT  Feed-in-Tariff
FYM  Farm Yard Manure
HTC  Hydrothermal Carbonisation
ITT  Invitation To Tender
MES  Microbial Electrochemical Synthesis
PHA  Polyhydroxyalkanoates
POD  Points Of Digestion
POR  Points Of Recovery
R&D  Research and Development
RDI  Rapid Document Identification
REA  Rapid evidence Assessment
RHI  Renewable Heat Incentive
ROC  Renewable Obligation Certificates
VFA  Volatile Fatty Acid
WRAP  Waste and Resources Action Programme
**Figures**

**Figure 1** Rapid Evidence Assessment Methodology and Plan ..................................................3  
**Figure 2** The simple process of hydrothermal carbonisation when applied to a biomass slurry (from http://www.antaco.co.uk/technology/our-technology) ........................................6  
**Figure 3** Metabolic pathways of fermentation that can be exploited through the carboxylate platform for the biosynthesis of a range of commercially valuable products (from Agler et al., 2011) ..........................................................................................................................7

**Tables**

**Table 1** The process options identified by means of the global horizon scan and their potential applications in the UK AD market (those options selected for further study are highlighted in red) ........................................................................................................5
1.0 Introduction and background

The amount of organic waste treated by anaerobic digestion has doubled since 2009 when the UK Government published Shared Goals, which summarised its aspirations for uptake of AD in the UK (Defra, 2009). There are now 145 plants in the non-sewage sector treating around 11 million wet tonnes of organic waste annually\(^1\).

Although the digestion process destroys between 60 and 90% of the volatile solids fraction of the feedstock, the overall mass is conserved and so there is very little reduction in the actual volume of the digestate produced. Indeed since commercial operators of digester facilities levy their gate fee for the waste received based on volume, the waste producers increasingly are compacting this waste and thus it will require diluting before feeding the digester, in order to reduce the dry solids concentration. As a result the volume of digestate produced might exceed the volume of waste received. At present as much as 99% of the digestate produced in the UK is used in agriculture and horticulture\(^2\) and although it plays a valuable role in closing nutrient cycles, its financial value to the operator is low. Typically the haulage and spreading charges exceed the income derived from recycling this material. In addition, reliance on a single route leaves the AD sector exposed to significant risk, in particular for those operators that lack their own secure land bank; typically digesters processing food waste. Recent WRAP-funded reviews\(^3\) of alternative options for digestate enhancement suggest that the scale and throughput of commercial AD facilities are too small to warrant application of many capital-intensive enhancement and recovery technologies that can deliver digestate-derived fertiliser products; so called 'first generation enhancement technologies'.

There are, however, a number of second-generation technologies at various stages of development that may offer greater application. Many of these are based around the manipulation of digester biochemistry and microbiology to convert organic material in the waste stream into a wide range of high-value bioproducts, sometimes referred to as the Biorefinery Concept, the VFA Factory or in the concept of The Circular Economy, 'Extraction of biochemical feedstock'. Others exploit the ability of microorganisms to undergo electrochemical reactions either with the generation of energy through electrochemical fuel cells involving oxidative process, or by electrochemical synthesis resulting in the production of highly reduced chemical intermediates via reductive processes. There are also many non-microbial opportunities for instance those involving thermal processes that are able to achieve volume reduction of the digestate and provide an energy intensive final product.

All of these alternatives are at various stages in the commercialisation cycle, all with differing potentials for application to the UK waste AD market and all requiring differing resources to move them to a stage of commercialisation. Consequently it was the aim of this project to identify those innovative scientific and technological advances that offer the potential both to add value to digester feedstocks and digestate and to reduce or eliminate the volume of digestate remaining for recycling. The findings of this research are presented in a matrix format that is easy to assimilate and which will permit subsequent appraisal of those technologies identified, against a set of WRAP and Zero Waste Scotland defined viability criteria.

\(^1\) Anaerobic Digestion Market Update, available from http://www.eunomia.co.uk/reports-tools/anaerobic-digestion-market-update/
\(^2\) A survey of the UK Anaerobic Digestion industry in 2013 (ASORI) - See more at: http://www.wrap.org.uk/content/survey-uk-anaerobic-digestion-industry-2013#sthash.Y5upMr8n.dpuf
2.0 Précis of the method used

2.1 Methodology
The project sought to address both established and progressive technical solutions to improving digestate value. A ‘blue sky’ approach was therefore taken, which encompassed technologies that were still in an R&D phase or even defined only in theoretical terms in the academic literature.

Having such a wide remit carried the risk that routes to the research data would be uncontrolled, scope would expand and project deadlines would not be met. The Government-designed ‘Rapid Evidence Assessment’ (REA) research framework was therefore adopted to address these concerns. An REA is a systematic and documented process of searching for evidence, setting exclusion and inclusion criteria and data extraction from the materials found. Information might be sourced from peer reviewed or ‘grey’ literature and also drawn from primary sources by way of research interviews. The key principle of the REA is to set limits to research effort in order to optimise resources and allow the client to review performance during the life of the project. This ensures the most comprehensive research possible is undertaken within the given time constraints.

The REA for this study was built around the key research questions provided in the invitation to tender documentation (ITT) by WRAP, namely:

1. Current state of thinking – is the ‘option’ at the early research stage with no proof of principle or is it near to market?
2. Cost – how much will it cost to take the option to a demonstration stage and/or market?
3. Market size / impact – will the option have a high impact; is the technology a niche market or will it have a wider reach?
4. Adaptability – can the option deliver multiple results and across a range of plant sizes, or is it a niche option?
5. The value of the option and/or end product in terms of its environmental and commercial impact and how achievable their expected benefits are.
6. What is the likely impact on dewaterability and required end routes?

There are two principle phases to the REA: capturing the scope of evidence by means of a high level ‘rapid document identification’ (RDI) process (or ‘Global Horizon Scan’), and a subsequent, more detailed technical assessment of the products and processes (or options) to evaluate their potential impact and attractiveness. These phases are shown as Part 1 and Part 2 in Figure 1, and described in the following sections.

---

4 See http://www.civilservice.gov.uk/networks/gsr/resources-and-guidance
2.1.1 Step 1: Scoping of Research Themes

The body of evidence to be investigated was categorised within ‘themes’ so that boundaries could be set for the overall area of research as well as individual research tasks. The themes were reviewed regularly so that they could be reprioritised as required.

Themes were defined in this project as products and processes, which were already understood at a conceptual level, and were seen as having the potential to meet the requirements set by the research questions. The themes are as follows:

- **Heat and Pressure Based Technologies** – High temperatures and pressures in systems operated both at or below the critical point for water are widely applied to a range of organic materials to recover energy in the form of biochar (or biocoal), syngas and an organic rich liquid fraction. The heat can be applied via the conventional routes or using more novel options such as microwaves. Pre-treatment can also be applied to the organic material to enhance its subsequent thermal hydrolysis.

- **Novel Product Synthesis** – The range of products that can be produced by the fermentative reactions of digestion is large and these are often combined under the broad heading of the carboxylate platform.

- **Nutrient Recovery** – Several technology options are available for the recovery of nutrients, in particular phosphorus. These include simple chemical precipitation reactions, algal uptake and recovery and extractive P removal with membrane processes.

- **Waste Biorefinery Platform** – Biorefineries accept a range of feedstocks selected based on the chosen outputs of the biorefinery flow scheme. They can incorporate both biological and thermal degradation routes and usually involve nutrient recovery stream.
2.1.2 Step 2 – Development of Coding Strategy, Cloud-based Platform and Database
Coding of information sources is a critical element of the REA. The data collected were coded and organised onto OneNote©. This provides not only a full audit trail of the project for WRAP, but the database can also be further used and built upon to support any future studies in this sphere of research.

2.1.3 Step 3 - Rapid Document Identification (Horizon Scan)
This phase of the research involved, in the first instance, a review of the data already held by Aqua Enviro, followed by an online search of peer-reviewed academic journals, conference papers and a wider interrogation of more generic search engines.

A further tool, IVeredis, was utilised to supplement the aforementioned literature. IVeredis is an interrogation service, which provides up-to-date intelligence on new technologies, based on a series of questions set by the user.

2.1.4 Step 4-5 – Gap Analysis and Contact Strategy
The analysis of online conference and technical data allowed for a gap analysis to identify where it was necessary to contact key groups to discuss more recent research in the key areas and discuss future proposals.

2.1.5 Step 6 - Interim Report and Focusing of Further Research
A key milestone in the REA is to examine the strength of evidence collected at an interim stage before proceeding to detailed analysis and reporting. This resulted in the decision to proceed with the research, as it was felt that sufficient evidence was available to support a set of technical options that may help optimise digestate value.

2.1.6 Step 7 - Detailed Evidence Review and Synthesis
A detailed analysis of the technologies was undertaken, which resulted in the deselection of certain solutions based on technical or financial considerations. At this stage, processes that involve excessive capital outlay were eliminated. The remaining options being considered further involved either a high value product that can be extracted from the AD process, or an innovative AD process resulting in a digestate with associated lower management cost. Each product or process was extrapolated into a full end-to-end AD process flow, so that these could be compared on a like-for-like basis.

3.0 Evaluation of process options

3.1 The options found, their applications and research trends
Recovering resources from organic waste streams is currently a very buoyant research area with some clear trends that are driving research collaborations and providing the necessary funding. In turn it was clear that the marketplace is developing rapidly in response to both the UK government and the EU’s policy initiatives to develop a green economy. The evidence capture techniques employed in this study were still able to identify eighteen process technologies (Table 1) which might be applied either to add value to the feedstock or digestate, or to reduce the total amount of digestate that would require final recycling.
Table 1  The process options identified by means of the global horizon scan and their potential applications in the UK AD market (those options selected for further study are highlighted in red)

<table>
<thead>
<tr>
<th>Process Options by Technology Readiness Level</th>
<th>Adding value to Feedstock</th>
<th>Reducing Digestate Volume</th>
<th>Adding value to Digestate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discovery &amp; Research</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microbial electrosynthesis</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>PHA production</strong></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Micro algal growth</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwave hydrolysis</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macro algae (Lemnoideae)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Community by Design</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Innovation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Extractive Phosphorus</strong></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Recovery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electro-dewatering</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Demonstration</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Waste Biorefinery Platform</strong></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Hydrothermal carbonisation</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrolysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Carboxylate platform</strong></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Butanol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boerger Bioselect separator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advetec biothermic digester</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profi Nutrien ts BV</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Neo Energy (organic based fertiliser)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equares Clean Stream Reformer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Heat and Pressure-Based Technologies*

The main areas of research interest in resource recovery from waste are focussed on the potential of crops, in particular the second generation crops that do not compete directly with food crops. This also extends to crop residues with much of the effort devoted to releasing the potential of lignocellulosics either through conversion to energy or hydrolysis to simple sugars. The most common technologies involve some combination of heat and pressure, such as pyrolysis, gasification or hydrothermal carbonisation (HTC) (Laird et al., 2009). More novel approaches involve the delivery of heat through microwave technology. For both of these options, food waste and digestates have largely been ignored as potential feedstocks largely due to their high water and ash content. However biosolids have been a popular choice and generally with promising results that suggest certain of these technologies will work equally well with digestate (Weiland, 2011; Kim and Parker, 2008). As the relationship between heat and pressure, particularly around the sub- and super-critical water point, and its impact on the nature of the end-product became better understood, it is anticipated that the range of potential organic waste streams will increase. Hydrolysis routes to sugars have been achieved successfully through enzymic treatment or alkaline hydrolysis often in tandem with downstream thermal processing. Again however, few research groups...
or companies have specifically targeted food waste or digestate and have focussed on wastes with a larger carbohydrate fraction that consequently delivers easier rewards (Taherzadeh and Karimi, 2008).

Digestates are not the ideal candidates either for heat and pressure technologies or for lignocellulosic hydrolysis, as most thermal processes typically requiring a dry solids concentration of 70% or more. But HTC is unusual in that it is designed to accept wastes with a much lower dry solids (as low as 20%) and it is not troubled by the presence of high ash, nitrogen and other contaminants. Its main application has been in the conversion of biowaste to a carbon dense material with similar properties to fossil coal. The process takes wet and dry biomass, heats it to 200°C, pressurizes it to 10 - 20 bar and within 4 – 10 hours the biomass is converted into a dry, black powder (figure 2).

Figure 2 The simple process of hydrothermal carbonisation when applied to a biomass slurry (from http://www.antaco.co.uk/technology/our-technology)

The technology is available for application directly to feedstocks such as food wastes and in the UK it is being marketed by Antaco, who claim a carbon conversion of 90% (the fraction of carbon in the final product compared to the amount in the starting material). A by-product of the process is a liquid that is rich in soluble organic material. It was originally thought that digestate fibre would be an ideal feedstock for HTC with the potential to digest the organic-rich liquid fraction for additional energy recovery.

The further option of microwave hydrolysis which claims to convert digestate fibre into a sugar rich liquor has also been added for its potential within the context of a waste biorefinery platform (Keshwani and Chemg, 2010).

**Novel Product Synthesis**

The most active research area is in the application of microorganisms to generate a range of novel products. Fermentative anaerobes can synthesise a wide range of carboxyl compounds through what has become known as The Carboxylate Platform (Figure 3). Intermediates such as acetate, butyrate, lactate, succinate, butanol and ethanol can be
produced in short-retention time fermenters and with market prices for the end-products ranging from £840 to £2,400/tonne. Much of the work has been undertaken using pure bacterial cultures, which require a sterile sugar-based feedstock and sterile growth conditions to prevent contamination and with feedstock prices that are linked to the price of oil (Qureshi and Ezeji, 2008). The need to break this link has led to a major research initiative to generate sugars from waste lignocellulosics, predominantly crop residues but which could be easily extended to include digestate fibres. Recently researchers have recognised the benefits of mixed culture biomes to undertake carboxylate biosynthesis and whilst recognising yields will fall via this route, the opportunity to use other waste feedstocks under non-sterile conditions, may make process economics more favourable (Marshall et al., 2013). The Carboxylate Platform slots seamlessly into the flow train for most conventional food waste and FYM digesters and thus it has been selected for further evaluation.

**Figure 3** Metabolic pathways of fermentation that can be exploited through the carboxylate platform for the biosynthesis of a range of commercially valuable products (from Agler et al., 2011)

In addition to the fermentative route, novel materials can also be synthesised aerobically. For instance polyhydroxyalkanoate (PHA) is a microbial intracellular storage compound stored by certain bacteria when a growth-limiting compound, for instance nitrogen, restricts their growth but there is an excess of organic material available to them. In this case the
organic material is acetate and the bacteria can accumulate up to 70% of their cell mass as PHA (Akaraonye et al., 2010). PHAs are a precursor for a range of bioplastics and with a very high value. Work on digestate liquor suggests it is an ideal growth media for PHA accumulating bacteria, although it would need supplementing with acetate and sterilising (Pasanha et al. 2013). This process has been recommended for further evaluation as it fits well into the flow-scheme of existing digesters that dewater digestate for recycling the fibre, but with no economic route for removal of the dewatering liquor.

Microbial Electrochemical Synthesis (MES) was evaluated in some detail due to its novelty and the many claims made for its future potential. MES uses microorganisms to convert the chemical energy stored in biodegradable materials to direct electric current and chemicals. This is an emerging technology that claims to provide a solution for integrated waste treatment and energy and resource recovery, because it offers a flexible platform for both oxidation and reduction reaction processes. The anode chamber is a common feature of MESs processes in which biodegradable substrates such as wastes are oxidized and electrons generated and captured through an external circuit. These electrons are then used in the cathode chamber to drive any reduction-based reaction with the synthesis of value added chemicals, such as the carboxylates (Wang and Ren, 2013). At present much of the work has been undertaken at a very small scale on low solids systems. Results so far do not suggest this will scale up to high solid wastes over a realistic timescale or in an economic manner (Heidrich et al., 2014).

Nutrient Recovery
There is a broad consensus on the needs to reduce our usage of phosphorus since this is a finite resource without replacement and one, which is essential to successful and productive agriculture. It is also accepted that phosphorus use within a catchment is excessive and must be reduced in order to minimise risks of eutrophication in fresh water and marine environments. Phosphorus recovery from waste offers the opportunity to contribute to both of these needs and there is a vast amount of research being undertaken worldwide to achieve this. Phosphorus can be recovered through precipitation usually in the form of magnesium ammonium phosphate known as struvite. It can also be recovered biologically through the growth of both micro- and macro-algae on the phosphorus rich dewatering liquor. But both of these options are operationally complex and capital intensive, recovering what is essentially a relatively cheap resource (Shu et al., 2006). As the concentration of phosphorus in food waste is low at around 1.2kg P₂O₅/tonne, then a digester treating 50,000 tonnes could only recover 60 tonnes of P₂O₅ a year. Of course other wastes such as farm yard manure have much higher concentrations of phosphorus, however the quantities of material treated tend to be significantly less. Consequently a cheaper and simpler option is required and membrane separation technology appears meet this requirement, although still at a very early stage of development. For this reason it was selected for the short list. A further option for recovering phosphorus that also made the short-list was Neo Energy organic based fertiliser. This simple process uses excess heat together with some of the electricity from the CHP system to dry the digestate to a granular form. It has been commercialised in the US with the granules being marketed to golf courses as a high value material offering a range of benefits. In this case it is not the technology itself that is most of interest, but the business model and marketing strategy that is being used to sell the granular product. A similar approach in the UK, if applied successfully, would have a big impact on how digestate is perceived in the market.

Waste Biorefinery Platform
The processes reviewed up to this point, have a high capital cost. The technologies for production and extraction of the end products of the carboxylate platform, bioplastics production and P recovery require a high volume of waste to make the technology economically viable i.e. in excess of 100,000 tonnes. Such quantities are unlikely to be
found within an economic radius of most sites. The Biorefinery Concept utilises many different organic feedstocks including both organic wastes and renewable biomass. It also integrates a range of processes to convert these feedstocks to fuel, power, materials and chemicals. It is a multi-stage process in which each production stream is converted into a co-product stream rather than a waste stream and consequently it has no waste outputs, only products. The technology is defined by the nature of the material it receives and a number of Biorefinery Platforms have been proposed. The two best-known biorefinery platforms are: i) the sugar platform, in which purified enzymes convert biomass into five- and six-carbon sugars as intermediate feedstock chemicals that are converted further by, for example, fermentation to fuels, and; ii) the syngas platform, in which thermochemical systems convert biomass into syngas (i.e. synthesis gas, such as CO, H$_2$ and CO$_2$) as feedstock chemicals that are converted further by, for example, catalysis to fuels (Kiran et al., 2014).

A full-scale facility has been constructed recently at Billund in Denmark and is now operational. It receives sewage sludge, municipal organic waste and industrial organic waste and when fully operational it is intended to recover energy and phosphorus and produce bioplastics and compost as outputs as well as a purified liquid stream. Biorefineries are likely to play a central role in the green economy of many European countries and they have advanced research programmes to deliver these. At present there is a growing body of work on a waste biorefinery platform strengthened recently by publications such as the March 2015 Building a high value Bioeconomy paper. This offers the UK the opportunity to take a lead in this area and on this basis it was added to the short list.

3.2 The options selected for further evaluation
The initial list of technology options (table 1) was reduced to a short-list of six based on an assessment of how well they complied with the list of six desirable attributes described in Section 2.1.

The six options that were selected for further evaluation covered all parts of the Technology Readiness Cycle and in addition could contribute to all the desired process attributes. These options in order of their commercial readiness are: Integrated AD Fertilisers; hydrothermal carbonisation (HTC); carboxylate platform (lactic acid); membrane phosphorus recovery; Waste Biorefinery Platform. A full process description and flow sheet for each option is embedded within the selection matrix which includes an individual evaluation and scoring of each option against the list of WRAP selection criteria.

---

4.0 Discussion

4.1 Production of novel products

The recovery of resources from organic crops and wastes is a large and developing research area globally receiving a lot of attention from the academic research community and benefiting from significant funding at national and European level. As a result there are many exciting technologies at various stages of development that could potentially be of value if applied to the treatment of organic wastes. The existing flow sheet for the anaerobic digestion of food waste and farm yard manure requires only minor changes to accommodate many of the promising processes identified in this report. The Carboxylate Platform if applied to the production of acetate, lactate, succinate, butanol or ethanol, requires only a short retention digester of three days or less, operating upstream of the existing facility. The digestate from this reactor is then dewatered to around 12% dry solids and the solids stream is passed forward to the existing digester for methane recovery. The carboxylate-rich liquor then passes to a subsequent treatment stage. It can either be extracted for its carboxylates, or it can be utilised directly for the production of PHA in an aerobic treatment stage. Both these options of extraction and PHA production will require significant capital investment and expertise in new equipment.

But in the UK the quantities of food waste are quite small when compared to energy crops or crop residues with typical food waste digesters treating from 20,000 to 60,000 tonnes. The largest facility at ReFood Doncaster, despite a significant expansion recently, will still handle only 160,000 tonnes. Although the quantities of farm yard manure are much greater nationally, the amounts handled at an individual facility are small. Thus those innovations that result in the generation of a novel product will necessarily be limited by scale and the larger the facility, the greater the chance of a process proving economically viable. The break even figure will depend on the market value of the product and at present this is largely unknown. For instance taking the carboxylate platform described above as an example, it is reasonably straightforward to generate a digestate with an acetate concentration in excess of 60,000 mg/l or 60 kg/tonne feed. As the quoted market price of acetate is £750/tonne, then in theory this adds a value of £45/tonne of feedstock. The capital costs of a digester to achieve this will be small as it requires a retention time of three days or less, but the capital and operating costs of extracting and purifying this acetate will be significant and it is this stage that is likely to provide the economic hurdle.

An alternative is to transport the dewatering liquor that is rich in acetate, to an existing local refinery (the UK has four major chemical centres at Grangemouth, Teeside, Saltend on the Humber and Runcorn), or a new central refinery receiving digestate from a number of digesters through a network of PODs (points of digestion) and PORs (points of recovery). In order to bring these technologies to market there are a number of outstanding knowledge gaps:

- What is the maximum concentration of carboxylate that can be achieved through undefined mixed cultures using food waste and farm yard manure as feedstocks and which of these has the highest market value in the UK marketplace?
- What is the minimum tonnage of product at which on-site extraction becomes feasible?
- Is there interest at existing refineries in accepting carboxylate-rich liquor and what would be the value of this liquor?
- At what tonnage of product does a dedicated Point of Recovery become feasible and can this quantity of product be economically provided.

Answering these questions is not challenging, but clearly it requires a consortium approach. The UK is one of the world’s top chemical producing nations with a value of over £27 billion
and employing around 214,000 people. Thus taking this approach to develop novel products is a good fit with existing expertise. UK Trade and Investment are closely involved in levered investment to the sector and a logical consortium partner. In addition a member of the UK Speciality Organic Chemicals Sector should be involved to provide expertise on extraction and recovery processes. A suitably funded consortium should provide these answers in a period of two years or less.

4.2 Recovery of phosphorus
An economically viable process for the recovery of phosphorus is hindered due to the low costs of the final product and the small quantities that are available for recovery at existing facilities for digestion of food wastes and farm yard manures. Membrane extractive P recovery is at an early stage of development and would be aided by pump priming to establish its future commercial potential. Its likely strengths will be in its ability to isolate a number of valuable products (acetate, phosphorus) from digester waste streams from a mixed membrane process. At this stage it is some way from market but a small project with its aims clearly focussed on demonstrating market potential, would establish whether the technology had a future and warranted further investment. A part of this small project should be to establish other benefits arising from P recovery that can be internalised, such as enhanced digester performance, reduction in nuisance precipitation and reduction of P load to the catchment. The second phase of investment that is needed to move from the laboratory to demonstration, is likely to be substantial.

Drying and granulation of digestate to recover the phosphorus in this form is established technology although the costs of doing this in the UK and the implication for using energy in this way on RoCs, FiTs and RHi are not established. The knowledge gap is to establish a likely value for this material within potential speciality markets.

4.3 Hydrothermal carbonisation
This simple process fits easily into the existing digester flow scheme (figure 2). Where a facility has dewatering with an established route for handling the dewatering liquor (for instance through aerobic treatment with recirculation of the treated effluent), the HTC can be utilised to carbonise the fibre to produce an energy rich biocoal and an organic rich liquor for recycling and energy recovery through the existing digester. For those facilities, which at present do not dewater their digestate, HTC offers an opportunity to eliminate this final product. Digestate is generated at around 4% dry solids whereas HTC requires a dry solids of between 15 and 25%. This provides an opportunity to take in additional feedstock, ideally at a dry solids >25%, to use in admixture with digestate and raise its solids to the required range. This additional material might be more food waste, green waste, energy crops or crop residue. The knowledge gaps for commercialisation of this technology are:

- When used on digestate fibre, what is the energy value of the biocoal and how much additional methane can be recovered from the liquid fraction?
- Does the liquid fraction have a detrimental impact on the digestion process?
- What are the potential applications of biocoal and what is its value in these applications?
- When used on whole digestate what is the best material to use in admixture to raise the dry solids?

Many universities have the necessary bench-scale facilities to undertake HTC on a range of admixtures to produce the biocoal and organic-rich liquor. The potential energy value of the liquor can be determined by means of the biochemical methane potential (BMP) test protocol. However considering the potential of this technology it is more appropriate to undertake all of this work at a demonstration scale and the technology provider Antaco, have
a demonstration scale unit that is able to undertake this. A carefully prepared experimental study of around six months duration, should prove adequate to fill the knowledge gaps.

4.4 Waste Biorefinery Platform
The majority of the technologies investigated during this study show a reduction in payback period as the quantity of waste processed increases. However many plant operators already struggle to source adequate waste for their existing facilities with little opportunity to increase this amount. At the same time a major issue in exploiting the potential value of digestate, is the necessity within each process to dewater the digestate and then recycle the liquid stream. The Biorefinery Concept is perhaps the only approach which resolves these problems as it accepts organic wastes from a wide range of sources, for instance: food waste, FYM, energy crops, crop residues, and in the absence of the regulatory hurdle, sewage sludge. In addition, the technologies that make up the Biorefinery ensure that both solid and liquid fractions are fully recycled. All of the technologies described in this section could form part of a Biorefinery and its flow train will be a bespoke solution suited to the available waste streams and required product output. At present however the Waste Biorefinery Platform remains a concept and although the individual process options that form its flow train have been validated in the laboratory a large amount of optimisation and scale-up work is required before an ideal process can be developed. The initial capital costs for a commercial biorefinery are also high and estimates of the feedstock needed to make the process viable range from 1,000 to 7,000 tonnes per day. However, there is a general agreement amongst the research community that this is a long term vision of how organic wastes and second generation crops could be handled. What is required at this stage is a vision for the development of the Biorefinery within the UK, in a similar way to the Defra Shared Goals vision that was so helpful in driving forward the uptake of food waste and farm yard manure digestion.
5.0 Conclusion

- A range of search techniques have been applied to identify eighteen novel options at various stages of Technology Readiness Level, that might be applied to the UK Waste AD Market to add value to the feedstock; reduce the digestate volume or add value to the digestate.
- Using a Rapid Evidence Assessment approach, six of these processes were short listed based on their potential for commercialisation, when assessed against a list of process attributes provided by WRAP.
- A decision matrix has been prepared to allow WRAP to systematically analyze, and rank these options in a quantitative and transparent manner, against a set of weighted criteria and thus identify the option(s) that warrant funding through to a commercialisation stage.
- The processes selected ranged from those simply requiring a market evaluation (Neo Energy) to assess potential viability, those that require proof of concept on food waste derived materials (hydrothermal carbonisation) through to more ambitious, internationally leading techniques that require a UK vision for their adoption.
- The UK has an internationally leading chemical industry that is a major contributor to the economy. It should be playing a more active role in developing the potential of novel product recovery from the fermentation of organic wastes and its inclusion in future collaborative research plans is recommended.
- For all of the process options scale is the key element that will determine commercial success and the larger the facilities the more opportunities it has for adopting innovative technologies. There is a paucity of novel ideas for adding value to small-scale digestion facilities.
6.0 References


Defra (2009) Anaerobic Digestion – Shared Goals

*Eunomia (2014)* Anaerobic Digestion Market Update - Addressing the Feedstock Famine


