Final Report Summary - END-O-SLUDG (Marketable sludge derivatives from sustainable processing of wastewater in a highly integrated treatment plant)

Executive Summary:
The safe treatment of wastewater is one of society's most fundamental challenges. Wastewater treatment creates sewage sludge, the processing of which is highly energy-intensive, contributes to greenhouse gas emissions, and is still far from efficient. Scientific investigations and technical developments have focused on five critical areas of sludge management with the ultimate aim of achieving a holistic system solution for sustainable sludge management.

- **Sludge reduction investigations:** Dissolved Air Flotation was investigated as a method for reducing the volume of sludge produced. Pilot scale trials of the novel process showed that improved TSS removal produced 59% reduction in the organic load to the activated sludge process, a common secondary wastewater treatment step, with a concomitant reduction in the power requirement.
- **Sludge treatment investigations:** It has been found that using inverted phase fermentation watery sludge could be split into separate solid and liquor fractions which could be converted to biogas in smaller more efficient digesters reducing the capital investment considerably. Furthermore, the digested solid fraction could be treated by micro-milling to break down the sludge matrix further releasing biogas during a secondary digestion resulting in 75% overall organic to energy conversion. Yet, a significant breakthrough was made with the discovery of BIOPOL, a crude biopolymer product derived from digested sludge. It has been found that BIOPOL could provide an excellent alternative to struvite formation as a co-precipitation method for phosphorus recovery from sludge liquor.
- **Downstream processing for sludge derivatives:** The greatest challenge of the project was to design, build and test a process for making a fertiliser product with sludge cake to exact specification which includes many physical, chemical and biological parameters. The new process makes use of CHP and other sources of waste heat to produce a granular, free flowing, dust free product known as OMF with a guaranteed nutrient content.
- **Market development activities:** Tests showed that the prototype OMF product could be spread accurately with twin spinning disc fertiliser spreaders up to a bout width of 24 metres, a respectable performance. In farm scale trials the OMF product gave similar yields to conventional fertiliser when applied to cereal and grassland crops. Market data, technical performance results together with the product safety data and environmental findings have been collated to provide a substantial body of evidence in support of the case for End of Waste for OMF as a new sludge derivative.
- **Management and sustainability studies:** Sustainability assessment methods have been developed and used to compare a number of options for sludge management across Europe. The comparative study showed that under certain scenarios OMF has great potential to be a sustainable option for sludge management with best social, economic and environmental benefits. The methodologies and learning from END-O-SLUDG have been pivotal in the development of a long term sludge management plan for Asturias (Spain).

Overall END-O-SLUDG has made considerable progress in developing innovative holistic solutions for sludge treatment and management including life cycle assessment and on-farm management of biosolids through to End of Waste.
Project Context and Objectives:
The safe treatment of wastewater is one of society’s most fundamental challenges. Wastewater treatment creates sewage sludge, the processing of which is highly energy-intensive, contributes to greenhouse gas emissions, and is still far from efficient. The impact of sludge management systems has to be carefully addressed in the context of EU energy policies, climate change mitigation, and resource efficiency policies. This project researched, developed and demonstrated a toolkit of novel processes together with market development for advanced sludge-based products and integration methodologies that could be applied to a range of wastewater treatment plants based on a typical municipal scenario. Supporting economic and life cycle assessment of the resulting gains in energy efficiency and conversion of renewable carbon, together with an implementation strategy based on a product mix with optimal value, were carried out in order to inform step changes that contribute to achieving more secure and sustainable sludge treatment and management practices in Europe while reducing pressure on natural resources and reliance on manufactured fertilisers. The concept of END-O-SLUDG represented a realistic response in Europe to deal with the rapid rise in sludge production and the need to address the public health, regulations, and the environment in the context of EU climate change mitigation and energy policies by moving toward maximum value recovery and end of waste. The main drivers were the reduction of carbon dioxide emissions (climate change), improving the security of the land recycling route and the economic opportunities thrown up by changing the technology basis of sludge production and treatment. Cognisant of the debate and public sentiment around the use of sewage sludge in agriculture, our project concentrated on developing and delivering marketable agricultural commodities as the end products to suit local condition. The five main distinguishing features of the project are:

(i) Objectives relating to sludge reduction:
One key aim of END-O-SLUDG was to utilise all the potential energy value in wastewater by maximising the recovery of carbon in the primary treatment step thereby minimising the energy required for aeration during secondary treatment and to minimise the generation of secondary sludge thereof. A number of activities were designed to achieve this aim, as follows:
- Enhanced solid removal: To identify the optimal conditions for >98% removal of colloids and suspended solids in settled sewage by novel dissolved air flotation (DAF) technique.
- COD removal: To identify the optimal conditions for >80% removal of dissolved organic compounds in the wastewater (after DAF) and their elution thereof using a range of commercial and custom-made adsorption media.
- Phosphorus removal: To identify the optimal conditions for >70% removal of phosphorus from enhanced biological phosphorus removal (EBPR) processes. Phosphorus is a finite resource and world supply is diminishing. On the other hand current sludge management practice often leads to phosphorus accumulation and a rise in the soil P index increasing the risk of water pollution.

(ii) Objectives relating to sludge treatment:
Digestion remains the preferred treatment option, however, with END-O-SLUDG we aimed to achieve stepped improvement in the biogas yield and significant process intensification to reduce the capital investment requirement and land takes. We sought to develop a practical low cost solution to the problem of pathogen re-growth in cake.
- Pre-treatments: To identify the optimal conditions for >80% conversion and recovery of the available carbon in sludge with improved sludge hydrolysis by enhancing the natural enzymic hydrolysis step with other physical augmentation treatments. Milling with grinding media and sonication with ultrasound will be investigated as a hybrid of the Enzymic Hydrolysis process.
- Inverted phase fermentation: The aim of this novel treatment step is to achieve fermentation of the sludge intermediate (after the pre-treatments) to produce a high strength organic liquor which may be used as a feedstock for biogas production or other industrial processes while simultaneously effecting at least 90% solid liquid separation.
- Digestion intensification: Employing Bio-granulation technologies for methanogen retention the aim is to achieve >98% methanogenesis of the sludge liquor (from the Inverted phase fermentation step) within 48 hours.
- Competitive exclusion: To identify the optimal conditions for introducing fast growing aerobic micro-organisms (friendly bacteria) into the residual sludge solids (after digestion process) so that they would consume any nutrients that may be released during any downstream processing steps, e.g. centrifugation, thereby avoiding possible re-growth of pathogens such as E. coli and Salmonella.
(iii) Objectives relating to downstream processing for sludge derivatives:
Sludge derivatives provide the means to deliver the maximum value of sludge. Different products are needed to cater for a range of markets with differing economic, social or geographical scenarios.

• Dewatering: Following on from the competitive exclusion investigation it was proposed to demonstrate the production and application of cake products derived from the competitive exclusion treatment using the centrifuges.

• N & P recovery: In the future, as a consequence of the new Water Framework Directive, additional total nitrogen consents are likely to be imposed by the regulators, driving up treatment cost further. END-O-SLUDG aimed to identify the optimal conditions for >90% ammonia removal using ion exchange and reverse osmosis.

• Production of bio-granules and organo-mineral fertiliser (OMF) Granulation: Development was focused on a two-stage process designed to produce a granular, free flowing, dust free product with guaranteed nutrient content (NPK of 10:4:4) using only waste heat.

(iv) Objectives relating to market development:
Our aim in END-O-SLUDG was to address the legal, techno-economic and market issues associated with the market introduction of the novel products, particularly the OMF. The work involved a number of activities including:

• End-o-Waste: To work with the relevant authorities on technical and legal aspects in order to develop new quality protocols for the new sludge derivatives, particularly the OMF, leading to the End of Waste status for these material streams.

• Product trials: To evaluate and demonstrate the use of sludge derivatives and a number of economically significant applications, in particular the use of OMF products and their yield potentials compared to conventional mineral fertilisers when used according to “good agricultural practices”. These farm trials will also look at the possible accumulation of phosphorus (P2O5) and heavy metals in the soil at recommended fertiliser application rates on selected European crops. Other trials will examine the use ammonium phosphate/carbonate in algal culture for renewable energy production.

• Nutrient management: To carry out further work to quantify the rate of nutrient release under different soil condition and to model the changes for the sludge-derived fertiliser products and to develop practical application protocols for their use in European agriculture. An information system will also be developed to incorporate the P-model and N-model to facilitate the management of nutrients for crops in a typical crop rotation system.

• Economic Assessment including willingness to pay, Risk Analysis, and SWOT. Individual assessments for each sludge derivative will be made. These will include process economics, resource issues, technology assessment, SWOT analysis, market potential evaluation, as well as issues resolved and recommendations for effective implementation. The results of these individual tasks will then be integrated for each relevant operation or sludge product, allowing conclusions regarding sustainability along the entire value chain to be made.

(v) Objectives relating to management and sustainability:
To achieve optimum economic, social and environmental benefit, END-O-SLUDG focused on concepts that utilise all the sludge resources, integrating processes for efficiency and managing the END-O-SLUDG sludge derivatives to best effect. These have mostly been described above; combining intensified conversion with novel process design and process integration is particularly important. In addition there are activities aimed at addressing issues affecting the effective application of the new products and analysing the marketplace for products in order to predict the best configurations for different economic, social or geographical scenarios.

• Pathogen risk assessment: To quantify the risk to human and animal health from land application of sewage sludge it will be necessary to improve our knowledge of the changing nature of the sludge products and the behaviour of pathogens from the point the products leave the sewage works. The investigation will include microbial ecology and population dynamics in the stockpiles or after spreading/ploughing; colonisation of pasteurised cake by harmful bacteria such as E. coli 0157 from livestock and the factors affecting the population dynamics such as rainfall, temperature, etc. This research will also incorporate advancements in pathogen risk assessment and communications made over the past ten years into a user-friendly methodology that allows pathogen risk assessment to be carried out more readily.

• Long-term soil impact assessment: Sludge recycling to land can only be sustained if the public safety, long-term soil health
and the quality of the environment can be assured. In order to improve stakeholder confidence in the practice this project will investigate the mobility and fate of phosphorus, heavy metals and organic micro-pollutants in soils. This research will incorporate advancements in risk assessment made in recent years into a practical methodology that allows individual risk assessment of the main contaminants to be carried out.

- **Technology Sustainability Assessment including LCA, EIA, SEA, Social, Political and Legal analysis:** Alongside the developments within END-O-SLUDG aimed at developing technologies and platforms and integrating them into END-O-SLUDG operations, a major objective is to assess the sustainability along the entire value chain. This will be achieved by a series of tasks that separately assess the major parameters relevant to making an assessment of sustainability over the entire value chain. These assessments are life cycle analysis, environmental (local) impact assessment (EIA) and strategic environmental assessment (SEA), social, political and legal assessment.

- **Integration methodologies and implementation strategy:** Develop suitable models for integrated END-O-SLUDG operations by optimising heat and mass balances and evaluating the conceptual basis of the theoretical models by comparison with the practical experiences of real industrial plants. Process economics, energy and material efficiencies, fuel qualities as well as market potential are also central issues here.

**Project Results:**

The END-O-SLUDG programme of work focused on the research, development and demonstration of a number of novel processes affecting the sustainability of sludge management in Europe. It has made notable progress in many of the critical steps in sludge management. Dissolved Air Flotation (DAF) was investigated as a method for reducing the volume of sludge produced. A pilot scale trial of a DAF plant in the Netherlands showed that by combining DAF with primary sedimentation overall TSS removal >99% was achievable. The improved TSS removal produced 59% reduction in the organic load to the activated sludge process, a common secondary wastewater treatment step, with a concomitant reduction in the power requirement. Significantly, a reduced organic load also means a corresponding reduction in the production of hard-to-digest surplus sludge resulting in at least 25% overall reduction in the volume of sludge requiring final disposal. Although reducing the volume of sludge is an important part of the solution, it can never provide the whole answer. Sludge will still be produced and need to be treated. Traditional digestion methods typically only release 45% of the potential biogas available. By contrast, it has been found that by using inverted phase fermentation, watery sludge could be split into separate solid and liquor fractions which could be converted to biogas in smaller more efficient digesters reducing the capital investment considerably. Furthermore, it has been demonstrated that the digested solid fraction could be treated by micro-milling to break down the sludge matrix further releasing biogas during a secondary digestion resulting in 75% overall organic to energy conversion. Yet, the Holy Grail for sludge management must be the end of any sludge requiring disposal. Instead, all sludge would be transformed into value-added products which could be sold for useful applications at a profit. Here the project has made a significant breakthrough with the discovery of BIOPOL, a crude biopolymer product which is derived from digested sludge. The digested sludge residue, made up primarily of various types of biopolymers, currently represents a huge untapped resource from wastewater in all developed economies. Most bacteria are Gram-negative and in activated sludge they account for over 90% of the bacteria strains. They have a relatively thin cell wall consisting of a few layers of peptidoglycan which make up about 10% of the biomass. Peptidoglycan is a unique biopolymer containing both D- and L-amino acids. Its basic structure is a carbohydrate backbone of alternating units of N-acetyl glucosamine and N-acetyl muramic acid. On the other hand, the intracellular components DNA and RNA account for about 23% of the dry mass of a bacteria cell, and that represents 18% of the digested biomass. Both DNA and RNA are composed of repeating units of nucleotides. Each nucleotide consists of a sugar, a phosphate and a nucleic acid base. The bases are hydrophobic and relatively insoluble in water at the near neutral pH of the cell. At acidic or alkaline pH they become charged, and their solubility in water increases. It has been found that BIOPOL could provide an excellent alternative to struvite formation as a co-precipitation method for phosphorus recovery from sludge liquor. BIOPOL has an estimated complexing or loading capacity of 41mg P/g (4.1% w/w) and very fast kinetics. As BIOPOL itself has a significant phosphorus content (6.5% P, dry basis), the resulting complex has an even higher P content (24.3% P2O5) which compares favourably with struvite (26.9% P2O5). The advantage of the co-precipitate as a fertiliser is the labile nature of the nucleic acids which would lead to rapid mineralization of the nutrients making them readily available to the growing crops. The production of BIOPOL as a new form of sludge derivative would provide a highly effective means for sludge management.
enabling the targeting of a phosphorus-rich product at farms most deficient in the nutrient while the residual nutrient-poor sludge could be recycled to arable land where organic matter tends to be minimal. Another key aspect of the END-O-SLUDG project is the pioneering use of Organo-Mineral Fertiliser (OMF) as a vehicle for End of Waste. It is crucial that sewage products are declassified as a waste material. While they remain so classified, they are subject to strict regulations governing their use, something which naturally undermines their practical appeal to farmers. Declassification would represent a crowning achievement for the END-O-SLUDG project – completing the final step in the process from sludge volume reduction through to the transformation of the sludge that remains into viable, marketable and safe end-products that meet stringent agricultural and environmental standards. At the end of the treatment and processing operation, the digested sludge cake is turned into safe, high-quality, easily transportable and spreadable fertiliser products. End of Waste is a complex legal process that enables the transformation of the waste into a product analogous to a raw material with the same characteristics as that of raw material and capable of being used in the same conditions of environmental protection. The END-O-SLUDG partners have worked together to produce the necessary evidence to demonstrate that OMF could replace common fertiliser products for crop production. Proving that there is a market demand relies on the assumption that everything being equal, the demand for the new product should follow a similar pattern as the conventional product. The greatest challenge, and indeed the bulk of the work, required the partners to design, build and test the manufacturing process to achieve a very exacting product specification which includes many physical, chemical and biological parameters. The new process makes use of CHP and other sources of waste heat to produce a granular, free flowing, dust free product with a guaranteed nutrient content. Tests showed that the prototype OMF product could be spread accurately with twin spinning disc fertiliser spreaders up to a bout width of 24 metres, a respectable performance and a significant achievement for the END-O-SLUDG team. In farm scale trials the OMF product gave similar yields to conventional fertiliser when applied to cereal and grassland crops. The application of OMF on the same soil for 5 years had had very little effect on the level of heavy metals and PTE’s and did not affect the earthworm numbers suggesting no adverse environmental or health impacts on the food chain. The market data, technical performance results together with the product safety data and environmental findings that have been collated constitute a substantial body of evidence which is due to be presented to the Regulators in support of the case for End of Waste status for OMF as a new sludge derivative. Further, tools and methods for sustainability assessment have been developed and used to compare a number of options for sludge management across Europe. The comparative study showed that under certain scenarios OMF has great potential to be a sustainable option for sludge management with best social economic and environmental benefits. The methodologies and learning from END-O-SLUDG have been pivotal in the development of a long term sludge management plan for Asturias (Spain). Overall END-O-SLUDG has made considerable progress in developing innovative holistic solutions for sludge treatment and management including life cycle assessment and on-farm management of biosolids through to End of Waste. A more detailed description of the main S&T results and foregrounds is given in the following five sub-sections.

(i) Sludge reduction investigations:

Conventional sewage treatment typically takes place in two stages. During the first or primary treatment step the wastewater is commonly treated in a series of settling tanks that remove the readily settle-able solids and give rise to the so-called primary sludge (PS). The settled sewage containing the dissolved solid fraction of the wastewater, colloidal matters and fine suspended solids is treated biologically in the second stage often by the activated sludge process (ASP). The ASP is very energy intensive because of the need to inject air into the process to meet the biological oxygen demand (BOD) of the wastewater. Sludge from secondary treatment known as secondary sludge or surplus activated sludge (SAS) or biological sludge is extremely difficult to digest. Typically, only 15-25% of the organic content of the SAS is reduced to biogas in the digestion process comparing to 55-60% for PS. DAF is very efficient in capturing fine suspended solids and colloidal matters. By removing the fine suspended solids and colloidal fractions from the settled sewage the organic load on the ASP could be reduced by up to 50% depending on the actual composition of the wastewater. This would result in a significant reduction in the energy requirement of the ASP. Furthermore, the DAF fraction would be easily digestible, more so than the PS, yield more biogas and less residual solid for disposal. The main challenge with DAF is the high level of energy required for the production of the white-water or microbubbles used in the process. END-O-SLUDG addresses this challenge with the use of GRAVITOX, a novel low cost aeration method that can be used for microbubble production using only a fraction of the energy needed in a conventional process.
Laboratory and pilot scale tests were done on wastewater that originated from the influent and effluent of the primary sedimentation plants at the municipal WwTW of Rijn & IJssel in Etten (The Netherlands). By combining a primary sedimentation step with a flocculation/flotation system, higher TSS, COD and TP reductions were demonstrated. The key results may be summarised as follows:

- An increase in TSS removal was achieved, from 25-66 [%] in traditional a primary sedimentation, and up to 95-100 [%] when combined with a flocculation/flotation system.
- Increase of COD removal from 6-53 [%] in traditional a primary sedimentation, and up to 39-79 [%] when combined with a flocculation/flotation system.

By combining a primary sedimentation step with a flocculation/flotation system, the chemical dosing requirements were reduced by a factor of 2X in comparison to a single flocculation/flotation system. An average COD removal of 59 [%] will lead to a similar reduction of aeration and electrical requirements in the aerated biological reactor that is placed after a combination of a primary sedimentation with a flocculation/flotation system. The removed TSS can be digested for the production of 0.15 [Nm3 biogas], delivering 0.38 [kWh] heat and 0.34 [kWh] electrical energy per [m3] of treated wastewater. Furthermore, an increase in TP removal was achieved from 7-15 [%] in a traditional primary sedimentation, ranging over 70 [%] when combined with a flocculation/flotation system. The phosphorus was removed with the sludge stream.

Further investigation was carried out with the integration of GRAVITOX and DAF system. The integrated system (Fig. 1) has been used to achieve suspended solids and COD removal from a stream of settled sewage. It has been found that:

- GRAVITOX reduces energy usage by 71 to 85 [%] compared to the power usage of the standard aeration system.
- TSS removals are in a range from 20 to 50 [%] with the lower limit of the FeCl3 dosage is in-between 15 to 19 [mg/l].

The investigation highlighted a number of challenges in the integration of GRAVITOX into the DAF process including the method of air injection into the GRAVITOX tube, distance between the GRAVITOX outlet and the flotation chamber, separation of coarse bubbles from microbubbles before introduction to the flotation chamber, and biomass growth in the system. However, it is believed that the problems are of a technical nature and could be readily designed out on larger systems.

Figure 1 schematic diagram of the integrated DAF / GRAVITOX system.

Overall, the present investigation has shown that the integrated GRAVITOX/DAF system provides a promising low energy method for the suspended solids and COD removal from a stream of settled sewage which could be used to reduce the organic load on the secondary treatment process in order to achieve reduction in energy consumption and sludge volume reduction leading to lower running costs for Wastewater Treatment Plants.

In a further investigation the settled sewage from Ellesmere Port Treatment Works has been characterized in terms of individual phase chemistries using Solid Phase Extraction (SPE) technique. The best phase chemistry for dissolved COD capture was found to be reverse phase followed by activated carbon adsorption and then strong anionic exchange. Based on the SPE results, commercially available media as well as biological media have been evaluated as possible biosorbents. In terms of COD capture efficiency and availability, Bio-flocs (SAS) proved to be the most promising biosorbent, with removal capacity of 14 mg COD/g VS and 38 mg COD/g VS for colloidal COD and total COD respectively. A novel process for the treatment of settled sewage using Bio-flocs as a biosorbent is proposed. In the proposed scheme FeCl3 is added as a coagulant to the settled sewage before contact with the Bio-flocs. The loaded Bio-flocs are then separated from the wastewater by the actions of a dissolved air flotation process. Expected reduction in soluble COD and total COD are 25% and 21% respectively. Such reductions should lead to a reduction in the power consumption in the secondary treatment step and an increase in
biogas production in the sludge digestion. Realistically, it may be expected that using Bio-flocs as a flocculent/bioadsorbent in conjunction with FeCl3 dosing in a DAF process for intermediate treatment of the settled sewage would produce a net energy saving of 25% in wastewater treatment while achieving phosphorus compliance under the Urban Waste Water Treatment Directive.

Phosphorus management has also been considered as part of the sludge reduction strategy. The investigation examined two new methods for phosphorus recovery from wastewater as options for phosphorus management. The use of FeCl3 as a coagulant in the DAF process resulted in enhanced P removal. Total phosphorus and orthophosphate removal for Ellesmere Port settled sewage were 35% and 29% respectively. The removal rates appeared to be a function of the influent P concentration as well as the ferric dose rate. The P content in the DAF sludge for Ellesmere Port was 12.6 mg total P per g dry solids of which 72% was orthophosphate, which would provide a good source of P fertiliser. Jar tests with the crude biopolymer BIOPOL extracted from digested cake material (detailed in the section below) confirmed that the new sludge derivatives were useful as a co-precipitant for phosphorus removal. Co-precipitation of orthophosphate using CaCl2 was most effective at pH > pH6.8 and a minimum Ca:P ratio of 3 (w/w). The new process proved useful for phosphorus recovery from concentrated phosphate liquor such as sludge liquor from EBPR process or digested sludge liquor. A recovery rate of over 90% was readily achievable for liquor streams with concentration over 100 mg P/L.

Co-precipitation using BIOPOL should provide an excellent alternative to struvite formation as a method for phosphorus recovery from sludge liquor. The new biopolymers have an estimated complexing or loading capacity of 41 mg P/g crude biopolymers (4.1% w/w) and fast kinetics. As BIOPOL has significant phosphorus content, approximately 6.5% P dry basis, the co-precipitated product (BioPHOS) would have a very high P content (24.3% P2O5) which compares favourably with struvite (26.9% P2O5). The advantage of the co-precipitate as a fertiliser is the labile nature of the biopolymers which would lead to rapid mineralisation of the nutrients making them readily available to the growing crops. Figure 2 shows a theoretical structure of the calcium phosphate-DNA complex.

The production of biopolymers as a new form of sludge derivative would provide a highly effective means for sludge management enabling the targeting of a phosphorus-rich products at farms most deficient in the nutrient and nutrient-poor sludge to arable land where organic matter tends to be minimal.

(ii) Sludge treatment investigations:
Biochemical Methane Potential Tests were carried out with samples of sludge from two wastewater treatment plants (WwTW) in order to evaluate the effect of the addition of conditioning agents and the effect of the “Inverted Phase Fermentation” (IPF) pre-treatment on methane production. Sludge A is a secondary sludge from a WwTW in which no primary treatment is applied and which has a high contribution of industrial wastewater. Sludge B was a mixed sludge from a WwTW employing primary and secondary treatment. The additives studied were: FeCl3 as coagulant and two polyacrylamides (cationic polyelectrolytes: “Chemifloc CH80” and “Chemifloc CH50”). The experiments were carried out under anaerobic conditions in 2L bottles. The VS inoculum/VS substrate ratio employed was 0.5. The inoculum employed came from mesophilic anaerobic digesters in which mixtures of cattle manure, sludge and food waste were co-digested. The volume and composition of biogas were measured over a period of 25 days. Concentrations of VS, TS, tCOD, sCOD, NH4-N were determined before and after the experiments and allowed us to obtain the specific methane productions (SMP) for the substrates.

The main results obtained were:
• The addition of FeCl3 had very little effect on SMP, which decreased from 246 to 242 LCH4/kgVS0 (sludge B). However, when expressing methane production in terms of volatile solids removed, the value increased from 496 to 541 LCH4/kgVSrem.
• The effect of the addition of polyelectrolytes to sludge A and B was different depending on the sludge type and on the
The SMP of sludge A varied from 255 LCH4/kgVSo when only adding FeCl3, to 248 and 358 LCH4/kgVSo respectively when polyelectrolytes Chemifloc CH80 and Chemifloc CH50 were also added. The SMP of sludge B varied from 242 LCH4/kgVSo when only adding FeCl3, to 302 and 269 LCH4/kgVSo respectively when Chemifloc CH80 and Chemifloc CH50, were also added. The increases were even higher if production is expressed in terms of volatile solids removed. SMP increased from 493 to 662 LCH4/kgVSrem (Chemifloc CH80) and to 612 LCH4/kgVSrem (Chemifloc CH50) in sludge A; and from 541 to 582 (Chemifloc CH80) and to 672 LCH4/kgVSrem (Chemifloc CH50) in sludge B.

- The IFP pretreatment enhanced SMP. The solid phase produced 296 LCH4/kgVSo, a higher value than that obtained with the sludge (246 to LCH4/kgVSo). The addition of FeCl3 had a negative effect, seeing as the SMP obtained was 276 LCH4/kgVSo.
- The presence of a polyelectrolyte in the sludge inhibited the IFP; no solid phase was separated in the upper layer.

The main limitations with sludge digestion are the poor gas conversion yield and the very long treatment period, both arising from the recalcitrant nature of the sludge biomass. Many of the pre-treatment technologies are able to provide significant benefits, such as higher biogas production as well as lower sludge disposal cost. Although the technologies are very different in their modes of operation, they all have the same aim: to increase the renewable energy production by increasing the volatile solid (VS) destruction. However, current best pre-treatment technologies only offer up to 65% VS destruction maximum. A two-part experimental investigation has been conducted to determine if advanced sludge pre-treatment techniques could be used to improve biomass utilization.

In the first part of the investigation ultrasound disruption and enzymic hydrolysis were applied to sludge samples from two wastewater treatment plants in order to evaluate the possible upgrade of hydrolysis.

The main findings are:

- As a general rule for ultrasound disruption, the greater the energy input, the higher the hydrolysis effect. However, there was a notable gap when applying ≈ 7000 kJ/kgTS with respect to the lowest energy input (≈ 3500 kJ/kgTS).
- Inverted Phase Fermentation (IPF) always increased the sCOD and NH4-N in both the SP and LP. The increase was greater in the SP than in the LP.
- Much higher solubilisation of organic matter was obtained when applying pre-treatments to secondary sludge. Energy inputs of 7000 kJ/kgTS achieved increases in sCOD of up to 34190%. IPF led to upgrades of up to 5140% in the LP and 21337% in the SP.
- The combined pre-treatments of ultrasound followed by IPF or IPF followed by ultrasound did not result in any extra advantage over the single treatments.

In the second part of the investigation micro-milling has been found to be an effective treatment for sewage sludge. In straight milling, the rate of COD release was 50% of the total COD for surplus activated sludge but only 17% for digested sludge. The effect of caustic milling of digested sludge appears to occur in two distinct stages, the first releasing approximately one third of the total COD and the second bringing about 100% dissolution of the total COD (Fig. 3).

Figure 3 – Rate of soluble COD release during the micro milling of digested sludge cake in 1% caustic (LHS) and digested sludge 5% caustic (RHS).

The solubility of the different components of the sludge biomass was found to be highly sensitive to changes in the pH and concentration of multivalent cations in the milled liquor. It was found that a change from pH11 to pH7 was sufficient to cause the precipitation of 70-80% of the soluble COD which was accompanied by a dramatic increase in the solution viscosity. A similar reduction in soluble COD and a viscosity increase were also observed with the introduction of multivalent cations such as Ca++ into the solution at alkaline pH. The soluble fraction of the milled liquor at pH7 could be precipitated by Ca++ addition.

The digested sludge residue, made up primarily of various types of biopolymers, currently represents a huge untapped
resource from wastewater in Europe. Most bacteria are Gram-negative and in activated sludge they account for over 90% of the bacteria strains. They have a relatively thin cell wall consisting of a few layers of peptidoglycan which make up about 10% of the biomass. Peptidoglycan is a unique biopolymer containing both D- and L-amino acids. Its basic structure is a carbohydrate backbone of alternating units of N-acetyl glucosamine and N-acetyl muramic acid. On the other hand, the intracellular components DNA and RNA account for about 23% of the dry mass of a bacteria cell, and that represents 18% of the digested biomass. Both DNA and RNA are composed of repeating units of nucleotides. Each nucleotide consists of a sugar, a phosphate and a nucleic acid base. The bases are hydrophobic and relatively insoluble in water at the near neutral pH of the cell. At acidic or alkaline pH they become charged, and their solubility in water increases. The interactions between DNA and metals, particularly the heavy metals, have been extensively studied. The binding of metals to the nucleic acids generally occurs through the formation of complexes. DNA represents a large variety of biological ligands for metals and could associate with metals after cell lysis. Biopolymers from sludge have many exciting possibilities, for example, they could be used as substitutes for polymers that are commonly used as flocculants/coagulants in municipal and industrial wastewater treatment. Work done under this project showed that using the novel micro-milling process, the biopolymers could be conveniently recovered as a product (BIOPOL) and used as a polyelectrolyte for the co-precipitation of phosphate from wastewater. BIOPOL has proved to be an excellent alternative to struvite formation as a method for phosphorus recovery from sludge liquor.

Given that 50% VS destruction is usually achievable with conventional digestion and that cell wall materials represent 15-20% of the digested biomass, assume that 50% of the wall materials could be fermented, the use of caustic milling as a pre-treatment for digestion could well result in an overall VS conversion rate of over 90%. Achieving total dissolution of the sludge biomass is a significant new breakthrough in sludge treatment technology and it is a critical step toward full utilization of sludge. However, there are still considerable challenges to overcome before such a goal could be reached. Conventional sludge digestion is typically very slow with 18-day HRT being the norm. Although pre-treatment technologies are available to enhance digestion, the best only offer 60-62% VS destruction maximum. A further two-part experimental investigation has been carried out to determine if advanced sludge pretreatment techniques could be used to reduce the HRT requirement and to increase the overall VS destruction rates (digestion intensification).

First, IPF was performed with samples of sludge, promoting endogenous enzymes at 42°C for 48 hours under anaerobic conditions. Enzymatic hydrolysis leads to a solid/liquid separation of the sludge. The experiments were carried out in mesophilic and thermophilic conditions in 5-litre Upflow Anaerobic Sludge Blanket (UASB) reactors, being semi-continuously fed. The co-digestion with crude glycerin was also studied. The main results obtained were:

- **Mesophilic digestion of the LP.** The hydraulic retention time (HRT) was reduced to 3-1 days, with organic loading rates (OLR) 6.9-18.5 g tCOD/L day. The methane production rate was maximum at 2.31 m3 CH4/m3reactor•day (Fig. 4).
- **Thermophilic digestion of the LP.** For HRT = 3-2 days (OLR = 6.4-8.2 g tCOD/L day), the maximum methane production rate achieved was 0.59 m3 CH4/m3reactor•day.
- **Mesophilic co-digestion of the LP with crude glycerin (1% v/v).** The HRT was kept at 3-2 days (OLR = 13.7-15.7 g tCOD/L day), but the methane production rate was maximum at 2.76 m3 CH4/m3reactor•day.
- **Thermophilic co-digestion of the LP with crude glycerin (1% v/v).** The performance was improved with comparison to the thermophilic monosubstrate digestion. However, it did not lead to better results than the mesophilic monosubstrate digestion: 0.91 m3 CH4/m3reactor•day, at HRT = 2.5 days (OLR = 13.1 g tCOD/L day).

![Figure 4. Methane production in the mesophilic digestion of the LP in 5 litre UASB reactors.](image)

In the second part of the digestion intensification investigation digested sludge cake was hydrolysed in a caustic solution with a micro-milling process before further digestion to enhance the overall methane yield per unit mass of sludge VS. Results showed that sludge pretreatment by micro-milling in a caustic solution resulted in the release of 50% sCOD (relative to tCOD) and a high biogas yield in digestion. Digestions were stable when pretreated digested sludge cake was used as a feed, and no inhibition or toxic effects to the digestion process were observed. Although current results show that the tCOD reduction was only 40% resulting from the 50% sCOD release by the micro-milling process, earlier work suggests that in the caustic milling of...
digested cake the total soluble materials account for 60% of the digested biomass, resulting in approximately 50% of the VS in digested sludge being recoverable as biogas (Fig. 5). These variations are likely to be due to variations in the digested sludge cake. Clearly, the actual performance of the micro-milling process in releasing sCOD would be dependent on the composition of the digested sludge and biogas generation would be dependent on the digestibility of the sCOD. For a typical 1:1 SAS to primary sludge composition, 50% VS destruction rate is expected during primary digestion followed by a further 50% reduction in the secondary digestion process after micro-milling, resulting in 75% overall conversion of VS to energy, a significant improvement over the performance of current advanced digestion technologies.

Figure 5: Biogas production in bench-scale digesters fed with digested sludge cake which has been treated by micro-milling at loading rates of 4.3 kgCOD/m3/day, 2.5 kgCOD/m3/day, and 1.0kgCOD/m3/day. Control chemostat fed with a non-pretreated digested sludge cake mixture.

Work on competitive exclusion was carried out to determine if it was possible to suppress the significant increase in the E. coli indicator number immediately after the dewatering operation of digested sludge. It has been suggested that E. coli re-growth due to nutrients made available by centrifugal actions is a risk factor in sludge recycling. This investigation focused on the development of a population of competitor micro-organisms, or probiotic culture, that when introduced into residual sludge solids, will reduce these nutrients within a very short period, preventing pathogens such as E. coli from colonising the cake.

Figure 6: Suppression of E. coli growth by different competitors in liquid culture
Screening performed on a range of sources identified a potentially suitable culture and its competition potential was assessed in laboratory-scale cultures (Fig. 6). In liquid cake extract medium E. coli growth in the presence of the probiotic culture was suppressed by up to 1000 fold, in comparison with the control. PLFA analysis suggests that the resultant phenotypes are sensitive to the culturing conditions. This offers the opportunity to create prescribed phenotypes suitable for suppressing E. coli. With further development there is a good possibility that the present approach could be implemented on industrial scale to suppress E. coli re-growth in digested sludge cake.

(iii) Downstream processing for sludge derivatives:
With the ever increasing demand and diminishing supply of nature’s resources it has become necessary to investigate alternative viable supplies of nutrients using novel methods and technologies. The present study looked at the feasibility of recovering sufficient quantities of ammonia and phosphate from wastewater treatment streams. The investigation took a two pronged approach to nutrient recovery; ammonia recovery by ion exchange and simultaneous recovery of ammonia and phosphate by reverse osmosis. The evaluation of commercially available ion exchange media yielded promising results where ammonium chloride solution was used as the feed for the ion exchange trials. A specific ion exchange medium was identified as having a greater affinity to ammonium ions, however further tests replacing ammonium chloride with Gravity Belt Thickener filtrate as the source of ammonia yielded disappointing results. Additionally performance of the ion exchange media diminished with successive ion exchange experiments. In conclusion, although initial results were promising, the feasibility of using ion exchange on a larger scale to recover ammonia is poor.

In the investigation of reverse osmosis technology, Gravity Belt Thickener Filtrate was initially passed through an ultrafiltration unit in order to remove a significant proportion of suspended solids, reducing the risk of membrane fouling in the reverse osmosis unit. The ultrafiltration permeate was collected and used as the feed stream for the reverse osmosis trials (Fig. 7). The effect of pH on membrane performance was examined. An increase of the feed pH from 7.28 to 8.52 caused a simultaneous increase in ammonia recovery and a four-fold increase in phosphate concentration. The results of reverse osmosis trials were encouraging, however further investigation would be needed to fully quantify the performance potential of this technology.

Figure 7 A Schematic of the Reverse Osmosis Unit Set up
On the other hand, the practice of recycling sludge to land has changed considerably over the years mainly due to legislation where the application of cake as a top dressing on pasture or arable land has become common practice. However, the
operation can cause public issues such as unsightly cake, slow cake breakdown and the occasional odour nuisance. Bio-granules offer a more attractive option to farmers and food producers but are costly to manufacture. A key aim of END-O-SLUDG was to develop a more energy efficient drying system for bio-granule production to ensure the product remains sustainable and economically viable. The proposed process comprises two stages: a granulation system to produce high quality green granules (60-65% ds) and a second stage where the green granules are dehydrated using packed-bed technology and low grade heat (Fig. 8).

Figure 8 Conceptual diagram of the two-stage process for bio-granule/OMF production.

A Lilliput plant was designed, built and installed at Ellesmere Port WwTW (UK) as a pilot system to demonstrate the production of bio-granules and OMF. After commissioning and start up, the Lilliput plant proved that it could produce spherical granules (Fig. 9). However, the crush strength, size and particle distribution were not compatible with fertilizer requirements. This was thought to be due to the novel nature of the plant, a downscaling of PUTTART technology that had not been attempted previously. In terms of economics, the cost of bio-granule production utilizing Lilliput was high. The requirement for thermal oil heating and two operators to effectively man the plant 24 hours a day meant that in this configuration at least bio-granule and OMF production was both financially and environmentally unsustainable. Even if the cost could be controlled and reduced to acceptable level, technical quality of the product suggests that in its current form the technology is not suitable for bio-granule production without significant further development.

Figure 9 Photo of the Lilliput pilot granulator at Ellesmere Port and a sample of the granulated product (bio-granules, inset).

Due to the inability of the Lilliput system to meet the production requirement, alternative production systems were considered. In order to produce bio-granules United Utilities’ own pilot granulator was re-commissioned. Pilot granulation was undertaken in parallel with the dehydration experiments. The static packed bed design is a key feature of the dehydration process (Fig. 10). Its main purpose is to avoid attrition in order to minimize fines and dust generation. The design also enables the use of any low heat grade hot air stream necessary to reduce the cost and carbon footprint of bio-granule production without compromising the quality of the product. Propane was used to simulate the source of low grade waste heat.

Figure 10 A schematic diagram of the dehydration process using waste heat and recycle heat

The main aim of the development work was to demonstrate the capability to achieve a free-flowing granular product with the correct physical attributes to facilitate good spreading with standard agricultural equipment. One of objectives was to produce enough bio-granules for spreading and to test a novel technology designed to reduce sludge drying cost through a two-stage production process. The results for the preliminary testing of the pilot bio-granules have been very encouraging (Fig. 11). The trials demonstrate that a two-step process involving cold granulation and dehydration is possible. The ability to utilize waste heat in this manner will simplify sustainable sludge drying. Further work is required to reduce the system heat loss to enable the process to operate at a higher temperature. It is believed that using temperatures of ≥65°C could vastly reduce the time required for dehydration. A prototype of the OMF product has also been successfully made in the two-step process and used in pot trials. The product created conforms to both the physical and nutrient parameters detailed in the end-of-waste specification (to be discussed below).

Figure 11 Photo of the pilot dehydration unit at Ellesmere Port and a sample of the granulated product (bio-granules).
The successful use of waste heat for dehydration significantly simplifies the production of bio-granules and will make the manufacture of OMF products more profitable and sustainable. The estimated unit cost of OMF was €162/t. It appeared that the greatest part of the unit cost is due to the supplementary nutrient input (53%). It is likely that further cost reduction could be made, for example through bulk buying of materials and effective odour control. The full scale plant design for OMF manufacture has been considered. In order to ensure OMF attracts a good market share, the product must remain uniform in both its nutrient value and physical properties. Thus the production equipment must remain stable and product quality monitored regularly. Nevertheless, the trials have demonstrated the possibilities and the next phase of OMF development should consider the up-scaled two-step process system, incorporating the lessons learned. It is suggested that work should now concentrate on discerning the capabilities of the dehydration system, and optimising cold granulation for better control of granule size.

(iv) Market development activities:

Much of the market development activities focused on the use of OMF in crop trials, which are essential in the development of the theoretical basis of nutrient management for the product. The data provide important evidence for the End of Waste case for OMF as well as the basis for the farmer-friendly application protocols for selected European agricultural crops. Further activities were also undertaken to evaluate the market and economic potential of new sludge derivatives in other applications.

Biosolids are commonly applied to land as a cake (25% dry solid matters) after digestion and dewatering. The dewatering process generates nutrient-rich liquor, which is normally returned to the head of the works for treatment, a significant cost burden. The liquor typically contains 800-1200 mg/L ammonia as N and phosphate in the range of 50-150mg/L as P. This corresponds to about 33% of the available nutrients in the raw sludge or approximately half the equivalent nutrients recycled to agriculture as cake or €117M worth per year of nutrients if they could be recovered. Work using an RO membrane has demonstrated that it would be possible to concentrate the liquor to produce a concentrate of ammonium phospho-carbonate, which would provide a fast-acting liquid fertiliser, ideal for grass silage application or pastures. However, further work is still required to evaluate the economic viability of the process. The initial plan of the project submission was to supply concentrate samples to Shell for work on algal cultures. However, Shell pulled out of the algal market during early 2011 and their role in END-O-SLUDG was taken over by Manchester University. The research that was subsequently carried out by Manchester University suggested that nutrient-rich wastewater may provide a sustainable means to cultivate microalgal biomass for biofuel use. Yet many microalgal strains are very sensitive to wastewater due to toxicity caused by abiotic and biotic stresses. Naturally adapted strains that can efficiently grow in wastewater effluent are therefore of interest, however, the mechanisms by which such strains tolerate wastewater conditions are unknown. The study isolated indigenous chlorophyte microalgal strains from a municipal secondary wastewater effluent tank. The strains were identified by molecular phylogenetics, and characterised by their ability to utilise exogenous organic carbon sources for mixotrophic growth and on the basis of their oxidative stress tolerance, in order to elucidate the mechanisms of wastewater adaptation. Two of the strains, identified as Chlorella luteoviridis and Parachlorella hussii, could grow very well in raw wastewater due to their substantial tolerance to oxidative stress, which is highly induced by the wastewater environment. These strains exhibited high ascorbate peroxidase activity allowing increased scavenging of reactive oxygen species compared to strains that are not well adapted to the wastewater conditions. Both strains displayed high biomass and lipid productivity values in wastewater effluent. The accumulated lipids were suitable for biodiesel usage with characteristics equivalent to palm oil- and sunflower oil-derived biodiesel. The strains were also efficient in nutrient remediation from the wastewater. These results demonstrate the potential of these two strains for future biofuel applications coupled to wastewater remediation and highlight the importance of oxidative stress tolerance as a key indicator of efficient wastewater growth.

The farm scale trials carried out in 2010/11, 2011/12 and 2012/13 focused on the response of agricultural crops to the application of OMF as a fertiliser. In the trials the OMF product (biosolids plus urea) was applied as a topdressing to winter wheat, winter barley, winter oats, spring barley, spring oilseed rape, spring beans, forage maize, and grass cut sequentially three times for silage. Over 20 replicated field trials evaluating the crop response to OMF fertiliser compared with inorganic nitrogen were carried out over the three growing seasons. The OMF and ammonium nitrate application rate was assessed to
provide the nitrogen recommendation calculated using the Fertiliser Manual RB209, which provides recommendations for agricultural crops based on soil type, average rainfall and previous cropping. The application rate for OMF was based on the total nitrogen content of the product. The majority of the field experiments was carried out at Broxton, Cheshire (Fig. 12) with some being undertaken at Harper Adams University, Shropshire. The experimental results showed that in nearly all situations the OMF gave similar yields of crops to those obtained from the application of ammonium nitrate fertiliser. The one exception was where OMF was applied as a top-dressing in April 2013 to spring barley and gave a significantly lower grain yield than when ammonium nitrate was used. These results show that application of OMF as a top-dressing, supplying nitrogen in the form of biosolids and urea, is providing adequate nitrogen to give full crop yields in the majority of situations. For spring-sown crops which grow rapidly and have corresponding high uptakes of nitrogen, the OMF should be incorporated into the seedbed before drilling or sowing to ensure improved availability of the nitrogen applied to the crop. The experimental work assessed the impact of repeated applications of OMF on the potentially toxic elements (PTE’s) or heavy metals in the soil and also evaluated the earthworm numbers in the soil as an indicator of soil health. Previous work has shown that earthworms can be sensitive to high levels of PTE’s in the soil. The level of PTE’s in the soil after applying OMF from 2007/8 to 2012/13 did not have a noticeable effect, and the levels recorded were less than 20% of the permitted legal limit in soil. The earthworm numbers on arable and grassland soils were similar where OMF and ammonium nitrate fertilisers had been applied. These results indicate that although there is concern regarding the impact of biosolids on the soil environment, this is not the issue that it was historically. The stricter discharge levels for PTE’s in biosolids imposed by the Environment Agency have had a major effect on reducing their potential impact on soils. The project has also assessed the ability of farmers to apply the OMF with commonly available farm machinery. Fertiliser spreader tests were carried out with OMF in two twin spinning disc fertiliser spreaders (Kuhn Axis and KRM Extrend, Fig. 12) which are used widely on farms in northern Europe. The spreader tests showed that the OMF fertiliser could be spread accurately up to bout widths of 24m. The low bulk density and shear strength of the granule did not allow accurate spreading at wider bout widths.

Crop trials carried out using OMF have so far indicated that there is no compromise to crop yield when compared to using an inorganic fertiliser. These trials provide some confidence on the potential fertiliser value of OMF necessary to meet crop requirements. In addition, OMF application has been shown to increase soil organic matter at least in crops such as grass. Soil analysis also indicates that there are some residual effects of phosphorus in soils, which can be taken into account by farmers for the subsequent year’s nutrient management plan. This may prove very valuable considering the limited phosphorus resources and the increased cost of inorganic phosphorus fertiliser. A challenge associated OMF and biosolids application to land is the threat of pollutant (as either heavy metals or organic micro-pollutants) accumulation in soil and eventually crops. Current work on potential accumulation of pollutants, however, indicates minimal impact to soil and crop. The outcome of the analysis of soils applied with biosolids over many years does not indicate significant build-up of pollutants, but this must be monitored in coming years to evaluate any potential changes in the future. Based on this there is a great potential for further extension of biosolids application to other parts of Europe where currently recycling of biosolids to land is low due to concerns raised by the public. This work goes some way to instil confidence and sets the scene for a potential increase in biosolids application in other parts of Europe. However this has to be complemented with regular monitoring of pollutants in soil and crops to ensure that all safety procedures are adhered to in a strict manner. Harmonised policy guidelines on pollutants permissible in soils associated with biosolids application will be valuable to support the initiative of increasing biosolids recycling to other parts of Europe.

Currently in Europe the cost of sludge treatment and disposal is a considerable part of the revenue expenditure incurred by all sludge producers. The production and commercialization of sludge derivatives are attractive to sludge producers not only because they provide new income streams, but since they also reduce the cost of disposal of any sludge residues. A holistic sustainable sludge management vision appears to be within reach, with the prospect of reduced sludge volume requiring disposal, increased energy output and a portfolio of marketable sludge-derivatives, making the expected impact of END-O-SLUDG on the EU economy very significant. The nutrient replacement value of sludge is approximately €60 per tonne, but
Currently there is a supply/demand imbalance in favour of the consumers. Since sludge production is relentless, the only way to affect the supply of sludge to the market is to channel it to different outlets. Bio-granules and OMF are differentiated products sold into different market segments. Their production would reduce the availability of sludge cake in the market, eventually driving up the price of cake close to its true value. In Europe it is estimated that less than 10% of sludge produced is processed by thermal drying. This is due to the energy intensive nature of the process. The bio-granule market in the UK is now well-established, with Anglian Water and Southern Water the major suppliers. Prices of this granulated product can vary according to the fertiliser market; currently bio-granules are sold for about €30/t (at roughly 50% of the nutrient value, but well below the manufacturing cost of €130/t). It is estimated that a potential agricultural land area of 800,000 ha in Europe could benefit from OMF application, creating a market for 800,000 tonnes OMF per year. While offering a nutrient value of €127 per tonne, OMF currently costs €162/t to manufacture, however, there is good scope for further cost reduction.

END-O-SLUDG is regarded as a realistic response to deal with the rise in sludge production in Europe and the need to address the impacts upon public health, regulations, and the environment in the context of EU climate change mitigation and energy policies by moving toward maximum value recovery and ‘End of Waste’. The criteria for gaining End of Waste status are presented in Article 6 of the European Union Waste Framework Directive. It is clear that a key issue in the development of the ‘End of Waste’ case will be its potential deployment across Europe and to overcome such issues the substantive legal case must be developed based on the overarching European law. A qualitative review of the key waste streams produced through wastewater sludge treatment has demonstrated that OMF shows the greatest potential to obtain End of Waste status. However, at this stage OMF is not being produced as part of a defined production process. Notwithstanding this we can conclude that:

• OMF has a discernible market potential, potentially allowing it to meet the key requirements that define End of Waste status.
• End of Waste status is possible for the OMF materials produced through the two-stage process.
• Similar product streams have achieved End of Waste status in the recent past.

As part of the development of quality procedures to determine when OMF generated from sewage sludge has gained End of Waste (product) status, preliminary material specifications have been derived for both inputs to the recovery process and the final product outputs. These material specifications will define when materials entering the process are acceptable and after processing, when they have met the required standards to be considered fit for purpose as fertiliser products and that they pose no greater risk to the environment and human health than comparable products already existing in the market place. These specifications, together with market data, technical performance results, product safety data and environmental findings, constitute a substantial body of evidence due to be presented to the Regulators in support of the case for End of Waste status for OMF as a new sludge derivative.

(v) Management and sustainability studies:
Management and sustainability studies were concerned with factors controlling colonisation and persistence of harmful bacteria (using E. coli as a model), from the point at which the sludge reaches the farm, and incorporating the results into a risk-assessment model. Experimental work and literature reviews have also been undertaken in an assessment of risks to the environment and public health resulting from sludge recycling to land using data from the studies of soil P dynamics, heavy metals and polyaromatic hydrocarbons build up in soils. In addition, LCA, EIA, SEA and other methodologies for technology assessments were made in order to take into account the whole value chain and sustainability issues to determine the optimum sludge management strategy with due consideration of any geographical factors.

Several issues pose serious risks to the land recycling operation of sludge, including odour nuisance, and contamination with heavy metals and pathogens, factors which directly impact on public confidence. Pathogens can be released to the environment following sludge application, leading to contamination of crops and nearby water sources, which then act as transmission vectors. This can have serious health implications for both humans and livestock. Therefore it is crucial that interactions between soil, sludge and potential contaminants are investigated with a view to reducing this risk. Soil is an important determinant in regulating pathogen survival, and factors including texture, structure, pH, moisture, temperature,
UV, nutrients, oxygen, land management and biotic interactions can significantly influence microbial dynamics. However, if pathogens enter the soil protected within the sludge matrix, they may be protected from environmental extremes. Thus viable pathogens can potentially contaminate crop and water supplies, and be transmitted to humans and animals, thereby constituting a significant health risk. Laboratory studies showed that clay content is an important factor that can influence pathogen survival, and that the effect of sewage sludge may vary, depending on the mineralogical composition of the soil and the pathogen type in question. This should be taken into account when assessing the survival capacity of pathogens introduced to the soil environment via sludge application. A key focus of the project was to determine the importance of sewage sludge loading (i.e. proportion of sludge to soil) on pathogen dynamics. However, microcosm studies conducted with both laboratory strains of E. coli and Salmonella, and indigenous sludge-derived E. coli indicated that there was no significant association between sludge loading and survival. Further work looked at the effect of amending sludge and soil microcosms with energy-rich substrate, in order to stimulate microbial activity and maximise the probability of microbial interactions between soil and sludge communities. This highlighted that glucose, a simple carbon source, increased competition for other nutrients required for cell propagation, leading to a greater decline in E. coli. Collectively, these results indicate that pathogen survival can vary depending on soil and sludge parameters. Additionally, attempt was made to predict such a risk. The following section describes modelling the risk of pathogen transmission associated with land application of sewage sludge.

There is considerable variation in the pathogen content of biosolids, ranging from very low concentrations <10^1 CFU/ml in treated biosolids, up to 107 CFU/ml in untreated biosolids. There are few studies on the survival of introduced biosolids derived pathogens in soils after land application. The few data that exist suggest that biosolids derived pathogens should decrease rapidly after land application. The pathogen content of treated biosolids varies depending on biosolids treatment process and can be unculturable post treatment. The pathogen content of biosolids should be known prior to land application. Environmental factors such as temperature, moisture, soil type/clay content have been shown to effect pathogen survival post land application. Higher temperatures and low soil moisture have been shown to increase pathogen survival post biosolids application (Fig. 13). In other words pathogens proliferate longer under cool and moist conditions. Soil factors such as organic matter content and clay content have been linked with pathogen survival in soil. High clay content and higher organic matter contents have been associated with the survival of introduced pathogens. Soil nutrient availability has been positively linked with pathogen survival, which may also be involved in pathogen survival in high organic matter soils. The UK Safe Sludge Matrix provides a robust framework for the use of biosolids in agricultural systems. Biosolids are an important source of nutrients such as phosphorus, nitrogen, potassium and other trace elements. The Safe Sludge Matrix recommends that all biosolids are treated to reduce pathogen content by over 99% using a range of treatment processes. In contrast animal slurry and manures used in agriculture rarely undergo treatment to reduce pathogen content and introduce a significantly higher pathogen loading to the environment.

Figure 13 Monte Carlo analysis of soil E. coli concentration in the soil (CS) following biosolids application to land.

Application of sludge to land still raises cause for concern especially in relation to accumulation of heavy metals and organic micro-pollutants. The literature on heavy metal and organic micro-pollutant concentrations in soil at sites receiving sludge for many years or that have had sludge applied many years ago was reviewed. For heavy metals, only sites in the UK and Europe were considered. However, due to a lack of data for organic micro-pollutants from long term sites in Europe, information from Australia and the USA were considered as well. The sites in the UK were Woburn Market Garden Experiment (1942-1961); ADAS Historical Sites (including Luddington and Lee Valley (1968-1991)); ADAS Long Term Sludge Experimental Sites including Woburn, Rosemaund, Gleadthorpe, and Bridgets (all in England, 1994-2007); and Hartwood and Auchincruive (both in Scotland). Sites in mainland Europe include Braunschweig (Germany, 1980-1989); Askov, Denmark (1973-1979); Pamplona, Spain (1993-2009); and Ultuna, Sweden (1956-present). The literature review considered the impact of sludge application on heavy metals and organic micro-pollutants in soil and its consequences to plant and soil microbial community. The main finding from the review was that concentrations of total and ‘available’ metals tend to increase in soils receiving sludge. However, the pollutants present in sludge do not pose a significant threat to crops and even if there is crop uptake, the levels do not exceed regulatory safety limits. More direct impacts can be seen on soil microbial communities and it has been reported
that heavy metals in sludge, mainly Zn and Cu have caused significant reductions in microbial biomass, nodules of N2 fixing soil microbes and rhizobium. There has also been a shift in soil microbial diversity in a number of cases, indicating prolonged metal contamination. Generally, organic micro-pollutant concentrations returned to background concentrations within a year. There is some evidence of PAH accumulation, but this could be due to atmospheric deposition. Nonylphenols, LAS, and Triclosan generally decreased to background levels within a year. Uptake of these organic micro-pollutants by plants is considered to be negligible.

The experimental investigation involved the collection of soil samples from sites that have received sludge application for many years and to determine any residual effects of heavy metals and organic micro-pollutants. The sites chosen were part of a long term experiment conducted by ADAS in the UK and involved nine sites although at the time of sampling in 2012 only six sites were still active. The soil samples were collected and analysed for Cu, Cd, Zn, triclosan, poly aromatic hydrocarbon, nonylphenol and linear alkylbenxene sulphonates. These were indicator heavy metals and organic micro-pollutants that were chosen as part of a list of priority pollutants. The results show that since 1994, when the ADAS sites were commissioned, and during resampling in 2012, there were no heavy metals and organic micro-pollutants that were higher than legislative levels or in any alarming concentrations. This gives some assurance that over prolonged periods of sludge application to land, the impact of pollutant accumulation is minimal.

In END-O-SLUDG considerable effort has been made to consider the need to achieve sustainable sludge management, a great concern in Europe due to the conventional and traditional recycling options being progressively restricted by legislation. There are several groups of stakeholders who must welcome a particular management programme in order for it to be viable over the longer term:

- Farmers and other users of biosolids products must want to use the products and consider them safe and beneficial.
- The consumers and communities where biosolids are applied to soils must see the value and benefits and be willing to accept the occasional possibility of truck traffic or odour nuisances.
- The sludge treatment and disposal process must be financially viable for the sludge producers.

Sustainable development is a multidimensional concept with concerns in three broad themes: environmental, social and economic. Appropriate methodologies for technology assessment need to take into account the whole value chain relating to the specific sludge derivative, sustainability issues and geographical factors. The SUE-MOT programme appears to provide a flexible framework for sustainability assessment that could be adapted for the comparison of different sludge management options. The transparent framework encourages key decision-makers to systematically assess the sustainability of developments, taking into account scale, life cycle, location, context and stakeholder values. In particular, it provides an Integrated Sustainability Assessment Toolkit (ISAT) for sustainability assessment, which can bring together various metrics, models and tools to promote the required integration across issues, scales and within the decision-making process.

There are large numbers of tools that are well-established which could be used in ISAT. However many of these, such as LCA, whole life cost, and SWOT are more suitable for products, processes or options that are market-ready or close to market. Some, such as LCA, are particularly data-hungry and are not suitable for use with processes in the early stage of development, as is the case for many of those being investigated under END-O-SLUDG. Although each tool is capable of providing a systematic and methodological analysis of some of the issues, none alone could address all the priority issues of interest to stakeholders. Multiple criteria decision analysis (MCDA) brings all the issues together to achieve an integrated assessment by providing a platform that allows all interested stakeholders to interact and to reach a consensus on the issues. The results of the integrated assessment for END-O-SLUDG may only be regarded as preliminary since the option (OMF) is not fully developed and the MCDA exercise has not involved a wide population of stakeholders. Clearly the process could be iterative and would continue until a stakeholder consensus is reached. Nevertheless, it is encouraging that on all priority issues OMF appears to be more favourable than the conventional alternative, bio-granules.

The END-O-SLUDG project has developed a series of sludge derivatives that can be adjusted to suit local conditions, and whose
production is applicable to a range of wastewater treatment plants. With an emphasis on the whole wastewater treatment system, it provides an integrated approach to the development and implantation of novel products from sludge. Further, tools and methods for sustainability assessment have been developed and used to compare a number of options for sludge management across Europe. The comparative study showed that in certain scenarios OMF has great potential to be a sustainable option for sludge management, having social, economic and environmental benefits. The methodologies and learning from END-O-SLUDG have been pivotal in the development of a long-term sludge management plan for Asturias (Spain). The 25-year sludge management plan for Asturias has been produced using methodologies and lessons learnt through END-O-SLUDG and sets out how current sewage sludge management practices in Asturias could make the move away from landfill towards a more sustainable solution. The region of Asturias currently produces around 70,000t pa of sewage sludge. Of this total, over 80% is sent to landfill with the remaining 12% sent for recovery through composting. Current restrictions around legislations and the general topography of the area make spreading sludge to land difficult. With sewage sludge volumes expected to increase over the next few years, Asturias needs to adopt a more sustainable approach to sludge management. The plan recommends the introduction of technologies such as anaerobic digestion in the short-term, while other technologies developed as part of END-O-SLUDG to be integrated into the longer-term strategy.

Potential Impact:
While the majority of the technologies investigated under END-O-SLUDG have been successfully demonstrated at bench-scale, some have even been proven in pilot trials. However, there is work still to be done to remove any residual technical and commercial risks in a full-scale demonstration before the technologies could be rolled out. Nevertheless, a holistic sustainable sludge management vision appears to be within reach (Fig. 14). With the prospect of reduced sludge volume requiring disposal, increased energy output and a portfolio of marketable sludge-derivatives, the impact of END-O-SLUDG on the EU economy is expected to be very significant.

Figure 14 Vision of a holistic system solution for sustainable sludge management

Using the principles of Life Cycle Assessment Practice as described in the International Standards (ISO 14040-14043) we have built three systems models of wastewater treatment plants on different scales (5,000 person equivalents, 150,000 person equivalents, and 400,000 person equivalents) to quantify the comparative environmental impacts of the proposed END-O-SLUDG technologies. The boundary of the study is the wastewater treatment plant, focussing on the processes that change, and downstream to include sludge disposal by incineration or use on land as an organic manure/fertiliser, taking into account the fate of the carbon and nutrients in soil and environment. The functional unit is the treatment of sludge arising per capita based on inventories and data collected in the UK, Spain, and Northern Europe, but tentatively extrapolated to 80% of the European population. Sensitivity analysis was conducted to explore the model and the stability of data and assumptions. The projected annual European burden reductions of the combined END-O-SLUDG technologies are 78 million GJ or primary fossil energy, 6 million tonnes of global warming potential (100 year CO2 eqv), 33 thousand tonnes of eutrophication potential (PO4 eqv), 108 thousand tonnes of acidification potential (SO2 eqv), and 33 thousand tonnes of abiotic resource use (Sb eqv). However, sensitivity analysis has shown there are areas of important uncertainty in these figures. The most important caveat about these projections is that the crop-soil models are only applicable to English conditions and much of the data has been obtained under UK, Spanish, or Northern European conditions. Notwithstanding this, it is clear that the largest wastewater plants may well be the best places to target improvements with greatest impact.

The END-O-SLUDG Reduction System reduces all burdens with the exception of acidification on the largest plants, but is very sensitive to any saving in energy usage over the previous systems, and the need to maintain or improve phosphate removal from the effluent. There is technical speculation that it may remove so much carbon from the effluent that the activated sludge process changes and may require additional carbon. The activated sludge process is important for denitrification and some nitrous oxide loss (greenhouse gas) and this effect may not have been modelled. Downstream processing similarly reduces all burdens on average, but only applies to the largest plant. It is very sensitive, to the extent that it can discontinue...
the use of heavy fuel oil to run a thermal dewatering unit and use waste heat from the anaerobic digester biogas engines to achieve similar rates of dehydration. It is worth noting that the baseline would also be improved with the application of waste heat recovery technology, but for both systems waste heat is less available in Northern Europe and Scandinavia where winters are deeper and longer and district heating systems are more common than in the UK. Generally, the ability of farming to utilise additional nutrients without loss to the environment comes into question, as does the use of urea to improve the fertility and agronomic attractiveness of the new sludge derivative (OMF), resulting in upward pressure on acidification and global warming. Transport is never especially sensitive in the models, despite concerns about the fossil energy required for bulk haulage of sludge. Greater use of transport can be made if it helps find better uses for sewage sludge, such a ground better able to receive it. Overall, the systems model based approach to the Life Cycle Assessment of the END-O-SLUDG technologies has stimulated systems thinking and systemic insights during the iterative data-results cycle with the project. The work shows that reducing environmental burdens requires systemic interventions.

A high-level study has also been undertaken to apply the principles of traditional EIA and SEA techniques to identify and, if possible, help mitigate potential environmental and social impacts arising from the implementation of the proposed END-O-SLUDG concept. Potential impacts to human beings, fauna, flora, soil, water, air, climate, landscape (and the interaction between these factors) have been considered arising from five core areas of:

- Sludge volume reduction
- More efficient sludge treatment
- Downstream processing of high quality sludge derivatives
- Application protocols
- Assessment of pathogen risk and long-term soil impact

The strategic nature of END-O-SLUDG means that assessment has been designed to be relatively generic in nature, in effect providing a “scoping” of key issues arising through product development which would be addressed in more detail on a site by site basis once such development sites had been identified. In terms of application, the assessment also focuses on impacts likely to be applicable to the majority of potential use locations; should treatment be proposed for any particularly sensitive environments these should be addressed in further detail in subsequent assessments.

A number of options have been reviewed for which OMF is considered the preferred option. In general, impacts from OMF generation are considered likely to be managed through a combination of site-specific EIA and regulatory permitting of emissions, and no further work is required at this stage. Impacts associated with the use of OMF are generally considered to be the same as those arising through the use of inorganic fertilisers, with the exception of 1) an improvement in the resource use profile of the OMF, being an end-of-waste solution rather than an artificial fertiliser, and 2) the effects of micro-pollutants. The associated literature review on micro-pollutants in soil has concluded that whilst concentrations of total and ‘available’ metals tend to increase in soils receiving sludge, these “do not pose a significant threat to crops and even if there is crop uptake, the levels do not exceed regulatory safety limits”. Overall, therefore, no further impact assessment is deemed necessary from an EIA/SEA perspective over and above the other studies associated with this work as part of the regulatory approval process.

In terms of the political, legal, social, economic and geographic issues, a literature search was conducted to identify relevant evidence. This included a search of online scientific databases and all relevant legislation and regulations applicable to the use of sludge derivatives. Political impacts depend highly on the regulatory status of the sludge derivatives after treatment. In a best case scenario, it was concluded that gaining End-of-Waste status would result in less stringent guidelines, similar to those for current fertilisers. In a worst case scenario, it was concluded that application would be limited by the rules and regulations currently governing sewage sludge use on agricultural land. Social issues focussed on social acceptability of the product amongst consumers and the food industry, and the willingness and ability of the farmers to take on the risk of adapting and using the technology. Geographically, it was considered that the efficacy of the technology would depend on good supply chain development, minimising the costs of production, so that the OMF would be competitively priced against conventional fertilisers. On farm, as for all fertilisers, a range of geographically related issues were important, including prohibition of application on land beyond threshold steepness where contamination in water bodies is a risk, and on land at risk of being
floated, frozen, or snow covered. With regard to the legal and economic reasons which will make profitable the END-O-SLUDG project, the evolution of the law and the management that each country makes of their sludge production were considered. The project was also analysed according to future trends. The recycling of sewage sludge in agriculture has been regulated by Directive 86/278/EEC since 1986. The Directive addresses both pathogen reduction and the potential for accumulation of persistent pollutants in soils. It also sets maximum limit values for Potentially Toxic Elements (PTEs) in sludge or sludge-treated soil and specifies general land use, harvesting, and grazing restrictions to provide protection against health risks from residual pathogens. The Commission plans to undertake a comprehensive review of the provisions contained in the Directive 86/278/EEC. In the next 10 years the amount of sludge produced will be significantly increased. For this reason, in recent years in Europe, governments are trying to promote the End-of-Waste philosophy, seeking to turn waste into a useful, marketable and environmentally safe product.

The case for End-of-Waste status for OMF has been reported and the criteria for its achievement are presented in Article 6 of the European Union Waste Framework Directive. A detailed overview of the legal background to obtaining such End-of-Waste status has been presented. It is clear that a key issue in the development of the End-of-Waste case will be its potential deployment across Europe. To overcome such issues, the substantive legal case must be developed based on the overarching European law. A qualitative review of the key waste streams produced through sludge treatment demonstrated that OMF, a nutrient balanced sludge-based product in pellet form, showed the greatest potential to obtain End-of-Waste status. However, at this stage OMF is not being produced as part of a defined production process. Notwithstanding this, it can conclude that:

- OMF has a discernible market potential, potentially allowing it to meet the key requirements that define End-of-Waste status.
- End-of-Waste status is possible for the OMF materials produced through the END-O-SLUDG process.
- Similar product streams have achieved End-of-Waste status in the recent past.

The SWOT analysis considers the market Potential for OMF. The application of biosolids (sewage sludge) in EU member states varies considerably. In some countries a large proportion of biosolids produced by the water industry is recycled to agriculture, e.g. in the UK and Germany. In other member states biosolids are not recycled to agricultural land and incineration is the major source of disposal. Current recommendations for the application of biosolids to agricultural crops include cereals grown for animal feed (not being grown for human consumption such as milling, bread making, malting, muesli, porridge oats, etc.), oilseed rape, sunflowers, linseed and forage maize. They would also be suitable for use on energy crops, such as willow, miscanthus, wheat for bioethanol, maize or fodder beet for anaerobic digestion. In the UK biosolids are applied to approximately 1.5% of the cultivated areas, typically before combinable crops are established. Currently, in predominantly arable areas in the east and south of England, demand exceeds supply. A typical application for these combinable crops would be 100 kgN/ha, which would be supplied by 1 tonne per hectare OMF 10.5.0. Extrapolating the UK situation to EU member states gives the potential area of crops for application of biosolids of 40 million hectare and therefore a potential market of 40 million tonnes, but more realistically extrapolating from the current 1.5% of arable land in the UK that has biosolids applied gives a potential area of 600,000 ha in Europe (or 600,000 tonnes OMF).

Currently 39% of European sludge is recycled to agriculture, saving farmers €234M per year. However, in most cases the sludge products must be given free to farmers who are unwilling to pay for what they regard as a waste. The development of OMF is an attempt at product differentiation, to create products with on par performance to mineral fertilisers. Such a development is seen as an essential part of the commercial exploitation process. It would appear that only derivatives that are highly valued by customers would make a real difference to sludge management. A good understanding of the market potential (prices and volumes) of the novel sludge-derivatives is therefore a necessary part of the product development process. The production and commercialization of sludge derivatives are attractive to sludge producers because not only do they provide new income streams, but they also reduce the cost of disposal of any sludge residues. A holistic sustainable sludge management vision appears to be within reach, with the prospect of a reduced sludge volume requiring disposal, increased energy output and a portfolio of marketable sludge-derivatives, making the expected impact of END-O-SLUDG on the EU economy very significant. Another novel product, BIOPOL, is a specialty product intended as a substitute for polymers commonly used as flocculants/coagulants in municipal and industrial wastewater treatment. If BIOPOL is limited to just three applications, its relevant market size is probably ca. €900M annually. Further, the production of BioPHOS, a biological phosphorus product, could provide Europe with 618,000 tonnes pa (as P2O5), meeting 35% of the EU demand for P fertiliser.
The new bio-economy based on phosphorus recovery alone could potentially be worth €300M pa. However, given the vulnerability of the European phosphorus supply and the non-renewable nature of the commodity, it is likely that in the foreseeable future there will be price intervention in the phosphorus market, with financial incentives for phosphorus from renewable sources more likely.

The ultimate goal of the project is that sludge is considered a valuable resource, rather than a waste product. In considering the wider societal implications a Communications Plan was produced at the outset of the project focusing on five specific stakeholder groups:

1. Professionals working in the water industry: The water industry encompasses professionals working on wastewater treatment and sludge production and recycling. Sludge produced by the water industry is often considered a waste. The main aim of the project was to develop and demonstrate novel processes as options to provide improved treatment management of sludge which can then be adopted by the industry.

2. Academics: It was important that we communicate with scientists and researchers working in this field as they are often more able to tackle difficult problems in a disciplined manner and could provide more elegant solutions to the industry. Communication opens up opportunities for cross fertilisation of ideas which could also give rise to possible collaboration between industry and academia both now and in the future.

3. Farmers and agronomists: Ultimately the sludge based fertiliser products developed are destined to be used on agricultural land. The decision to use these products will lie with farmers and agronomists. Our communication with the farming industry centred on promotion of sludge based fertiliser products developed in the project.

4. Policy makers: Sludge production is a highly regulated business. Policy makers determine or can influence policy at a local, regional, national, European or even global level. We need informed policy makers who could provide the necessary legal framework which strikes the right balance between risk and benefit. Our communication targeted policy makers, government departments, government agencies and business leaders.

5. The general public: Ultimately sludge is an issue of society which we manage on behalf of the general public, whose acceptance of the solution is crucial. It is important that as the project progresses, achievements are presented in a way that would engage the public. This communication therefore needs to be accessible and relevant. Our key messages centred on improvements in sludge management, the products delivered and the consequent benefits to the consumers and the environment.

Throughout the duration of the project communications were developed to ensure that stakeholders were made aware of the objectives of the project and its achievements. The final dissemination task was to communicate, primarily to the general public but also to other interested stakeholders, the wider societal implications of the results of the END-O-SLUDG project.

List of Websites:
A website dedicated to the project– www.end-o-sludg.eu – was created in June 2011.

It has been the main point of contact with stakeholders and has been designed to cater for all of the targeted groups using a series of ‘tabs’ leading to pages providing specific information:

1. Welcome (home page)
2. END-O-SLUDG consortium
3. Sludge management
The first tab leads to the generic ‘welcome’ page which briefly describes the aims of the project and provides details on
funding and the contact details of the project co-ordinator. To provide continuity all future queries will be dealt with by the co-
ordinator. The second tab leads to information on each of the 14 partners. Tabs three-seven lead to information on sludge
management, technology, farming, sustainability and policy.

The website can be instantly translated using Google Translate and material produced by partners in languages other than
English will also be made available. This will allow communication with stakeholders who do not speak English.

The project website has been selected as the medium to communicate this information in accessible and relevant formats,
including videos, reports and research papers. Now that the project has ended the website has been overhauled and is now a
valuable source of information on the results of the END-O-SLUDG project. Information is presented in such a way as to be
accessible and relevant to the general public whilst providing greater detail should it be required. The website will be
accessible for a minimum of five years, providing a valuable legacy for the project. By providing levels of information in
increasing complexity, stakeholders of the website will satisfy simple curiosity or more specific information needs of all the
stakeholder groups.