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Towards a low-carbon economy

SLURRES 2017

Techno-Economic Review of the Market Potential for Development of a Slurry De-Watering & Effluent Treatment Technology Supporting Renewable Energy Recovery

A Research and Development Project Funded by the Sustainable Energy Authority of Ireland

Contents

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1. Executive Summary

This report assesses the technical and economic issues impacting the potential for deployment of a biomass-aided filtration technology to de-water livestock slurries. The objectives of the project included:

1) Identifying a technology that can be integrated into a continuous, low-cost process to de-water slurry solids, mobilising them for use as a renewable energy feedstock for Anaerobic Digestion (AD) or Advanced Thermal Treatment (ATT);

2) Identifying potential methods to improve recovery of nutrients, allowing them to be recycled in forms that optimise process economics and environmental sustainability; as well as

3) Reducing the environmental impact from slurry disposal, negating farm costs by reducing transport required for disposal, as well as addressing regulatory and technical issues increasingly constraining disposal via land spreading.

Livestock slurries are one of the most widely available and underutilised resources in Ireland. Current farming practice disposes of raw slurries via land spread, which precludes energy recovery and incurs a significant transport energy penalty. It results in sub-optimal nutrient recycling, giving rise to nutrient losses from fugitive atmospheric emissions and runoff to surface and groundwater. It contributes to agricultural emissions which are a pressing environmental concern that the State is finding difficult to address.

Slurries are identified as a potential renewable energy feedstock, and processing slurry for energy recovery may also mitigate environmental impact from the agricultural sector. Farm sector fragmentation, however, is a barrier to optimal deployment of energy-related capital infrastructure. This barrier can be overcome via a low-cost system to aggregate de-watered slurry solids, removing moisture to a level that makes transport for centralised energy/nutrient recovery economically and energetically viable. It is notoriously difficult, however, to secure efficient separation of solids in animal manures using standard mechanical separation technologies. This is due largely to the fact that solids are present in a colloidal suspension that binds separation technology such as fine mesh screen filters. Current mechanical filtering technologies use screens with mesh sizes above 1000 microns to avoid the build-up of impermeable filter cakes. This reduces solids separation efficiency and generates filtrates of a character that still generate excessive emissions when land spread. Alternative designs such as auger-driven screw presses use the auger as a source of pressure as well as material mobility, which in this context requires a compromise in process design that also results in sub-optimal separation efficiencies.

The SLURRES work programme investigated use of biomass filter-aids to improve efficacy of low-cost mechanical filtration for livestock slurry processing. To determine the impact that variations in filter-aid characteristics have on separation efficiencies, a bench scale mechanical filtration device was fabricated to test biomass aids of different structures and particle sizes. The investigation identified that under pressure, ligneous biomass such as sawdust maintained its structural integrity and corresponding permeability avoiding inhibition of the filtration process, whereas use of non-ligneous material such as corn cob particles could not maintain permeability and inhibited the filtration process. As expected, the tests confirmed that permeability decreased with a reduction in filter-aid particle size, and they further identified that a step-change in permeability occurred when as particle sizes were reduced below c. 400 microns.

The bench scale work informed design of iterative scale-up tests that investigated application of the biomass filter-aid concept to pressurised mechanical filtration for de-watering slurry samples. The project fabricated a rudimentary mechanical pressure-filtration device incorporating a manually controlled high-pressure pump to feed batches of slurry blended with filter-aid through two sintered metal filters. Sawdust was used as a filter-aid incorporating a variety of particle sizes that ranged across the spectrum. This resulted in a symbiotic effect between the large particles that maintained permeability and a thin layer of smaller particles forming near the membrane which facilitated capture of smaller solid particulates within the slurry. Use of a filter aid comprised of multi-sized particles avoided requirements and costs in respect of comminution and particle separation. The scale-up tests demonstrated that the biomass-aided mechanical filtration removed a sufficient proportion of the slurry solids to change the character of the colloidal suspension in the filtrate, increasing viscosity as well as reducing the size of the residual particulates. This enabled deployment of a 2nd stage filtration, using calcium phosphate (CaP) crystals as the filter media, to clarify the stage 1 filtrate. The 2-stage process resulted in the removal of virtually all of the residual solid particulates, generating a clear (or slightly amber coloured) filtrate. It was theorised that the colour in the filtrate arose from dissolved ammonia and/or urea, which a subsequent analysis confirmed. The filtrate analysis also identified that total N content had been reduced from 2,600 ppm in the raw slurry to < 750 ppm in the filtrate. These results compare very favourably with the separation efficiencies available with current commercial separation technology, which is remarkable given the rudimentary nature of the filtration devices used in the tests.

The results suggest that a biomass-aided mechanical filtration process can be designed to provide a low cost means to separate slurry solids from liquors. Given the recalcitrant nature of the ligneous biomass filter-aid, the results suggest that ATT or adaptations of dry (or plug flow) AD may be best suited as an energy recovery technology. Results also suggest, given the particle-free character of the filtrate and the extent of N removal achieved during filtration, that a supplementary step to capture residual N may facilitate conditioning of the filtrate effluent to a standard that is immediately dischargeable at any period during the calendar year. This would address EPA concerns over losses to atmospheric emissions or runoff, mitigating environmental impact from land spread of raw slurry, and would also significantly reduce farm transport and storage costs, especially during the periods where land spread is restricted due to regulation or weather conditions. Process engineering and development work is required to engineer these results into a continuous prototype, to advance the technology to TRL 5-6.

If technology designs can minimise capital and operational costs, development of the technology may provide a low-cost means to aggregate slurry solids, overcoming the farm-sector fragmentation issues that constrain mobilisation wider use of the slurry resource for energy and improved nutrient recovery. Mobilisation of a large-scale slurry supply can potentially deliver a feedstock resource at little or no cost that can reduce the unit cost of renewable energy, which in turn may offer a means to reduce requirements for ongoing government subventions. Aggregation of the slurry resource for RES recovery at centralised locations may facilitate integration of improved nutrient recovery technology that may mitigate agricultural emissions.

2. Background

2.1. Sustainability Drivers

The EU's over-arching *EU 2020 Strategy* and Ireland's framework policy *Our Sustainable Future* recognize the inherent potential for leveraging development of "green" industries to mitigate environmental impact while delivering stable employment and economic growth. As part of a broader EU roadmap promoting transition to a sustainable low-carbon base, EU member states have agreed to binding obligations to reduce Greenhouse Gas (GHG) emissions by 20% over the 1990 baseline, and to source 20% of their energy demand from renewable resources by 2020.[1] These obligations will increase to 40% and c. 27% respectively, pursuant to 2030

[1] Renewable Energy Directive 2009/28/EC

Framework[2] proposals. Non-compliance with the binding obligations may carry a substantial penalty, that could cost as much as €3.5B Euros by 2030.[3] In addition to RES and GHG emissions frameworks the State is subject to obligations requiring preservation of the status of water and soil resources, as well as obligations to improve waste management and efficiency or natural resource utilisation. These sustainability measures are designed to mitigate climate change, improve health, wellbeing and biodiversity, and to enhance energy security and create jobs, delivering smart, clean growth that better reflects society's obligation to meet the needs of present generations without jeopardizing future generations' ability to meet their own needs.[4] Development of a system of energy recovery and nutrient recycling from the slurry resource will contribute significantly to these sustainability objectives.

Energy Decarbonisation - Ireland's energy requirements comprise 41% heating/cooling demand, versus 19% electricity demand and 40% transport demand. Energy decarbonisation objectives have been established for energy sub-sectors under the 2020 *National Renewable Energy Action Plan*, which include:

- 12% Renewable Heating / Cooling (RES H);
- 40% Renewable Electricity (RES E); and
- 10% Renewable Transport (RES T).

The majority of Ireland's heating demand is currently supplied either via natural gas or crude oil distillates. SEAI combustion emissions factors[5] highlight fossil fuels generate between c. 2.0 - 2.6 tonnes of $CO_{2\text{-eq}}$ GHG's for each tonne of fossil fuel combusted, whereas combustion of sustainably sourced biomass is considered carbon neutral (on a non-life cycle basis). Accordingly, Irish strategy to achieve its RES H objectives includes broader use of biomass resources to displace these fossil fuels, which is proving a challenge due, in part, to the diffuse nature of the national heat requirement.

As discussed more thoroughly below, de-watered slurry solids can potentially be used either as a solid fuel in ATT systems or can be used as an AD feedstock to generate biogas, which can be used in its dilute form once moisture and H_2S are removed, or further upgraded biomethane that can be distributed via the gas grid to supply the large established demand for gaseous energy. Each of the technology systems can be configured either as a boiler to supply RES H or as a CHP co-generation deployment to supply both RES E and RES H.

To transition the supply of heat to renewable energy sources, Ireland is considering imminent introduction of a Renewable Heat Incentive (RHI).[6,7] The current public narrative predominantly references small commercial scale biomass boilers to combust woody biomass as the RES H fuel of choice. Wood fuels, however, incur a substantial fuel cost (averaging c. €0.0397 per kWh_T of woody biomass) which will impact subvention requirements. Discussions with industry stakeholders indicate widescale deployment of individual biomass boiler applications may also be burdened by convenience and operational concerns, which may require an increased subsidy to overcome market inertia and incentivise wide take-up, especially amongst SME users where technical expertise may be lacking. Use of the SLURRES technology to supply dried slurry-biomass blends may offer an alternative feedstock that may potentially be widely available at a lower cost. Feedstock management, however, will be more intensive requiring closed-system receiving and storage infrastructure to

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[2] EU 2030 Climate & Energy Framework was adopted by EU leaders in October 2014.

[3] The cost may be €100-150 million for each percentage point shortfall of the 16% target, Sustainable energy Authority of Ireland (SEAI) estimate, 2014.

[4] Gro Harlem Brundtland's definition of Sustainability, http://ec.europa.eu/environment/eussd/

[5] http://www.seai.ie/Energy-Data-Portal/Frequently-Asked-Questions/data_and_data_manipulation_FAQ/

[6] Renewable Energy in Ireland 2013, February 2015 Report, SEAI

[7] Draft Bioenergy Action Plan, October 2014

comply with licensing or ABP requirements while the sophisticated ATT energy systems may require a greater degree of operator competence. Accordingly, deployment of ATT slurry-to-energy systems is likely to be suited for moderate scale industrial or community applications rather than smaller scale SME deployments. In respect of AD deployments, the current public discourse is focused on farm scale applications that could potentially be configured to integrate into the fragmented Irish farm sector. Tcbb RESOURCE reviews indicate that, provided a low-cost method is available to mobilise supply of slurry solids for digestion, the unit cost of energy may be reduced by aggregating de-watered solids for supply to moderate scale community digesters sited near to biogas demand or routes to market for biomethane, as these configurations can benefit from economies of scale and reduced costs for gas distribution.

Irish RES E strategy includes a wind-energy programme that can exploit Ireland's significant "free" wind resource to minimise the cost of RES E. Wind-energy, however, relies on deployment of large wind turbines for which it is increasingly difficult to gain public acceptance, as well as a variable wind resource that is unpredictable. A low-cost slurry-to-energy co-generation application can be designed to deploy either ATT solid fuel systems that either combust slurry solid fuels or thermally convert them to syngas, or alternatively use AD technology to convert slurry solids to a biogas energy carrier. Both systems are predictable and dispatchable, enabling contributions toward RES E obligations, even during base-load and peak demands when wind resources fall short. They can be deployed to meet either moderate scale private industrial demands where the RES E reference price is determined by the end-user supply price, or community co-generation requirements where the RES E is supplied to the national pool. If RES E outputs are supplied to the national pool, the predictability and dispatchability of the RES E outputs may address concerns over elevated pricing risks expected to arise from restructured balancing and capacity payments, as well as from the restructured reference price bidding process, anticipated under the new I-SEM RESS framework.[8]

Two-thirds of the energy outputs from slurry-to-energy co-generation applications are in the form of heat, divided into high-grade heat suitable for use as process heat and low-grade heat primarily suited to supply hot water and space heating demands. CHP economics dictate that both of the heat output must be valorised to optimise economic viability. Efficient utilisation of co-generation heat outputs also facilitates compliance with the High Efficiency (HE) criteria which is required to earn the highest level of State subsidies payable for the renewable electricity component. In 2013, circa 382,000 GWh of electricity and 2,900 PJ of heat were supplied across the EU by CHP plants deployed at sites offering a demonstrable heat demand and having access to heat distribution infrastructure.

The Irish economy is not heavily industrialised, which results in a lesser number of sites that require a large scale 24 X 7 heat supply. Aggregation of heat demand via construction of district heating networks may be one means to improve access to market outlets for heat. While Ireland does not yet benefit from well-developed district heat distribution infrastructure, many EU countries have demonstrated the benefits of district heating. In 2013, 20 mtoe of thermal energy was supplied via district heating schemes across the EU. Tcbb RESOURCE's review of the potential for community based renewable energy schemes[9] concluded that, from a societal cost-benefit perspective it could be beneficial in Ireland to co-deploy district heating schemes with waste/residue-to-energy applications in certain circumstances, including amongst others:

- An accessible annual thermal demand of > 2 MWh_{th} per trench metre together with introduction of measures that incentivise potential customers to connect to the district heat network;

[8] Public Consultation on the Design of a new Renewable Electricity Support Scheme in Ireland, Dept. of Communications, Climate Action and Environment, September 2017

[99] REBIOGEN: A Community Sustainable Energy Centre Model for Ireland, tcbb RESOURCE, Tipperary County Council, Tipperary Energy Agency, October 2017

- Introduction of measures to mobilise and aggregate local supplies of waste/residue feedstocks;
- RES H and RES E co-generation via low-cost waste/residue-to-energy applications that minimise feedstock costs;
- Availability of grid preferential grid connections, capacity and supply off-take provisions that underpin a stable RES E revenue stream derived from export to the national pool;
- Availability of EU grant aid subsidies that could match low-cost State financing for capital expenditure;
- Avoidance of gas network overbuild;
- Co-marketing of bundled heat and power;
- Introduction of moderate scale market supports for both RES H and RES E that operate in tandem to provide a stable revenue stream especially during early years when HE criteria may not be achieved.

The tcbb RESOURCE review highlighted that direct participation of the State as co-financier of community-based schemes may be the quickest and most assured means of achieving the State's RES and GHG mitigation objectives. It may also minimise the cost to the State, as a PPP financing structure could provide for remuneration on the State's exit, which would recover capital contributions as well as offset some of the costs of incentives, while providing a means to achieve the transition to market structures incorporated in EU state aid to energy policies.

New proposals under the new Renewable Energy Directive (RED II) may require that, to be counted against the renewable energy and GHG mitigation targets, certain forms of renewable energy will have to demonstrate a minimum level of GHG emissions savings calculated on a life cycle basis as well as comply with land use and indirect land use change criteria. Use of de-watered slurry solids as a renewable energy feedstock is likely to comply with these requirements (if ultimately adopted) and accordingly development of the SLURRES technology can potentially support contributions toward both RES E and RES H obligations, irrespective of whether technology deployments are configured for ATT or AD systems.

GHG Mitigation - GHG's are measured pursuant to a GHG inventory that is reported periodically against agreed 1990 baseline. GHG emissions are managed pursuant to 2 frameworks including the Emissions Trading System[10] (ETS) and a non-ETS framework. The ETS scheme applies to the largest GHG emitters pursuant to which they are obligated to progressively reduce GHG emissions or procure carbon certificates on the market under a 'cap and trade' principle; or face large penalties for non-compliance. Mobilising supplies of slurries and other residue feedstocks for RES recovery offers ETS obligated companies a feedstock source for renewable energy that can offset GHG emissions otherwise arising from combustion of fossil fuels. RES energy in the form of biomethane will be particularly beneficial to the industrial ETS sector, as the largest GHG emitters predominantly rely on gaseous forms of energy and require a suitable renewable energy carrier to meet the increasing obligations being imposed under the (ETS).

The non-ETS framework obligates individual Member States to manage emissions in sectors such as transport, agriculture and domestic/commercial energy. It requires the State to introduce policies and incentives that result in GHG emissions reductions, or purchase carbon credits on the market; non-compliance with binding obligations similarly results in imposition of large penalties by the EU. In Ireland non-ETS sector obligations arise from agriculture as well as transport and domestic/commercial energy utilisation, which generate c. 65% of Ireland's total emissions.[11] Current estimates suggest Ireland will miss its 2020 obligations by a wide margin.[12] Agricultural GHG emissions make up 32.6% of Ireland's total GHG emissions, among the highest in OECD.

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[10] EU Emissions Trading Scheme http://ec.europa.eu/clima/policies/ets/index_en.htm
11 Progress Toward Achieving the Kyoto and EU 20/20/20 Objectives, October 2014
12 Country Report Ireland 2015, Review on the Prevention and Correction of Macroeconomic Imbalances, 26.2.2015

Problematic agricultural emissions include methane from enteric fermentation as well as from manure management and the nitrous oxide derived from the turnover of nitrogen used as a fertilizer. These potent GHG's impact emissions by 21 and 310 (respectively) times that of CO_2.[13]

<u>Maintaining Water and Soil Quality via Nutrient Recycling</u> – Good agricultural practice requires farmers to adopt measures that maintain the quality of agricultural soils as well as reduce pollution of surface waters and ground water from agricultural sources. Good agricultural practice is enshrined in the Water Framework Directive (WFD) [14] which requires that the standard of surface and groundwater be increasingly improved to achieve "good" water quality status. In Ireland, where much of the surface water supply is at risk from Nitrogen and Phosphate fertilisers, this will require ongoing mitigation of the impact from intensive agriculture. Pursuant to the Nitrates Directive,[15] which aims to protect water quality from pollution by agricultural sources, all EU Member States are required to prepare a National Nitrates Action Programme (NAP) that outlines the rules for the management and application of fertilisers, including land spread of livestock manures. Until end 2017, Ireland's NAP incorporated a derogation that allowed, under certain conditions, application of up to 210 kg per Ha. of N to be applied to grassland pastures (versus a limit of 170Kg/Ha that applies elsewhere) which allows Irish farmers to land-spread slurries for periods other than from mid-September / mid-October through to mid / end January, depending on geographic zone. It is unclear whether this derogation will be extended for future periods. In Ireland, the NAP also governs levels of P that can be applied to soils.

Slurries incorporate plant nutrients including Nitrogen (N) that is resident in volatile/soluble inorganic forms primarily comprising ammonium/ammonia (NH_4^+/NH_3) and to a lesser extent nitrates (NO_3) that are immediately available for plant take-up. N is also resident in organic forms such as urea as well as in organic forms bound in the cellular matrices of the undigested feed (i.e. slurry solids). Liberation of these nutrients for plant take-up requires the intervention of soil microbiology that digest the organic carbon, and in the natural course of the N cycle converts the N to soluble inorganic nitrates that plants can utilise. Research reports indicate that urea is converted very rapidly (e.g. 3-7 days), while digestion of slurry solids continues progressively, causing N to be released over a much longer period.

When raw slurries are land-spread, unless application measures such as drilling are taken to reduce losses, a large proportion of the soluble/volatile N forms can be lost to fugitive atmospheric emissions and runoff. Teagasc reports that when raw slurries are surface spread on pastureland, up to c. 30% of ammonia is lost to atmospheric emissions with runoff accounting for a further loss of up to 30% (actual losses can be weather dependent). Similar losses occur as organic solids are digested and N is converted to soluble inorganic forms over the N cycle (although it is unclear from research if the level of this loss is as high as those experienced when ammonia is surface spread). This suggests that only 40% - 50% of the N value is taken up by plants.

Slurry also incorporates Phosphorous (P) that is principally resident in organic forms that are also bound in the cellular matrices of the slurry solids. Over the P cycle soil microbiology converts organic P to soluble inorganic phosphate, a large proportion of which is lost to runoff unless measures are taken to minimise losses.

Methods to improve nutrient recovery and recycling from slurries will contribute toward EU and State nutrient management objectives. To address environmental concerns arising from increasingly intensive crop fertilisation as well as supply risks in respect of phosphate fertiliser, the EU has recently published new

13 http://www.eubia.org/index.php/about-biomass/anaerobic-digestion
14 The Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000
15 Directive 91/676/EEC of 12 Dec 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources

standards in respect of organic fertilisers.[16] The recently proposed revisions harmonises EU rules for fertilisers derived from organic wastes and by-products, so as to open a cross border market for organic fertilisers. This is expected to underpin nutrient recycling that could substitute up to 30% of the more than 6 million tonnes of GHG intensive phosphate/nitrate fertilisers that are imported into the EU each year.

The proposed regulations address a range of fertiliser categories, and establish minimum criteria required to be met in order to be labelled as a CE compliant fertiliser. For example, to be classified as an Organic Fertiliser, the product must be contain carbon and nutrients sourced solely from biological sources, and must not exceed specified maximum levels of certain elements (e.g. Cadmium (Cd) < 1.5 mg/kg DM, Hexavalent chromium (Cr VI) < 2 mg/kg DM, Mercury (Hg) < 1 mg/kg DM, Nickel (Ni) < 50 mg/kg DM, Lead (Pb) < 120 mg/kg DM, and Biuret (C2H5N3O2) < 12 g/kg DM). The product must be free of *Salmonella spp* and must not contain *E. Coli or Enterococcaceae* at > 1,000 CFU / g fresh mass. Manure is considered a Class 2 Animal By Product under ABP regulations,[17] and provisions of the organic fertiliser proposals apply regulations that require ABP exported off of the host farm lands to be treated at 70 C^0 for a minimum period of 1 hour to minimise the risk of bio-contamination on disposal. Further provisions govern the input materials that can be acceptably included in CE labelled fertilisers, which exclude use of municipal sewage sludge as a component of organic fertiliser.

Low-cost methods to efficiently aggregate slurry solids will facilitate not only energy recovery, but also exploitation of the nutrient recycling opportunity. Energy recovery from slurry solids is most likely to be undertaken either via AD or Advanced Thermal Technology (ATT may include either pyrolysis or fluidised bed combustion). These technologies provide opportunities to incorporate nutrient recycling initiatives. If processed via AD, slurry aggregation will provide the scale necessary to make both AD and digestate pasteurisation economical, whereas the prospects of covering these costs from applications scaled at an individual farm scale would be less likely. Depending on how prices for organic fertilisers evolve, aggregation may also provide the scale necessary to remunerate the cost of drying and pelletising the fibrous digestates, which can generate a fertiliser product capable of supplying both nutrients and organic carbon to assist with maintaining soil quality. Dried pellets would be easily stored and shipped, offering a product in a form that can be used indigenously or exported.

If slurry solids are processed thermally, they will generate either an ash or biochar product. The high temperatures achieved in tthermal processing will address bio-hazard concerns in accordance with ABP regulations. Thermal processing mineralises the feedstock P and K in the biochar/ash residues as it drives off the volatile components, including C and the organic N, in the gaseous emissions. It also concentrates the feedstock metals in the char or ash. Accordingly, recipes will have to be evaluated to determine how saleable blends can be formulated that comply both with organic fertiliser proposals and with REACH or other regulations that govern land spreading of materials exhibiting certain chemical (metal) concentrations.

Resource Efficiency, Circular Economy Principles and Rural Economic Development - Energy recovery and nutrient recycling have been prioritised in EU Circular Economy Policy.[18] *Food Harvest 2020* references the potential contribution that efficient use of agricultural resources can make toward sustainable economic development. Fragmentation of feedstock supply is one of the constraints currently burdening wider development of the renewable energy sector, particularly in Ireland. Livestock slurries are potentially valuable

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[16] Proposal for a Regulation on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009

[17] EC Regulation no 1069/2009, Animal By Products Regulations

[18] Report on Critical Raw Materials and the Circular Economy Brussels, 16.1.2018 SWD (2018) 36 final PART 1/3 COMMISSION STAFF WORKING DOCUMENT

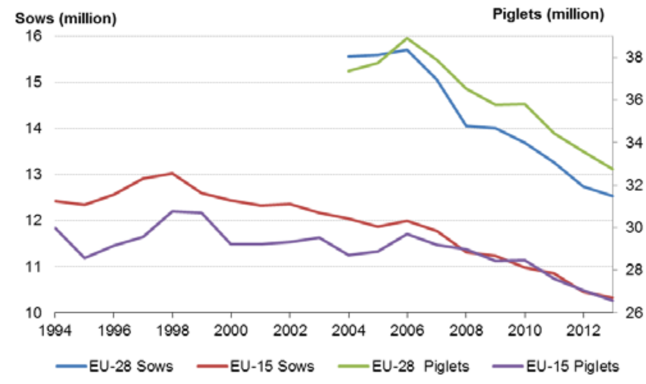
resources that are widely available and currently under-utilised. The farming sector, however, is highly fragmented which precludes mobilisation. A low-cost method to aggregate livestock slurries as a feedstock for RES applications can create the scale that, in turn, can incorporate other elements of the ABP supply chain, creating a virtuous cycle of scale and much needed efficiencies overcoming the fragmented nature of the supply chain. Mobilising pig slurries can potentially reduce the significant cost of slurry management, contributing to the competitiveness of the industry. Mobilisation of cattle slurries, the largest individual component of the potential Irish ABP supply chain, will become increasingly important in the face of potential dairy herd increases/farming intensification expected on the back of lifting the milk quota.[19] While Irish dairy and beef farmers typically have land banks for disposal of their slurries, intensification including an increase in stocking rate will require a means to mitigate the environmental impact arising from slurry disposal, thus avoiding environmental constraints that may otherwise limit growth in the sector.

2.2. Slurry Supply and Current Disposal Practices

Ireland generates large volumes of pig and cattle slurries that have been identified as potential feedstock resources for renewable energy and improved nutrient recovery. Current farming practice in respect of slurry management reverts to land spread as the lowest cost means of disposal, which also recycles plant nutrients and provides a source of organic Carbon to condition agricultural soils. Different market circumstances arise in respect of managing pig versus cattle slurries that have implications in respect of their respective availability for energy recovery.

The Irish pig breeding herd comprises some 150k sows, while the breeding herd across the EU28 is some 10.5M sows. Sows and progeny are generally housed indoors which means the resultant slurries are available in concentrations at scale. A sow + progeny unit generates an estimated 18 MT of slurry per annum, resulting in a respective annual disposal requirement of c. 2.7M MT (120k DMT) in Ireland and c. 210M MT (10M DMT) across the EU.

Figure 1: EU Pig Herd



Source: Eurostat 2015

Pig slurries are dilute, comprising c. 95% water and 5% solids. In Ireland, pig slurries are disposed of via contract haulage for land spread or in some cases via slurry ponds that periodically have to be maintained and treated. Anecdotal discussions with farmers indicate contract haulage and disposal costs can range from €6 - €8 per MT, depending on location and distance to disposal site. This results in a very substantial net cost for piggeries (e.g. estimated at c. €100k/annum for a modest 1,000 sow unit). Pig slurries comprise a significant Phosphorous element, which means that to avoid a build-up of excessive P levels in soils pig farmers require access to large land banks for continuous disposal via land spread. Increasingly stringent EU environmental legislation may curtail the practice of land spreading unprocessed animal manures going forward. Where farmers do not have access to a land bank, the concentration of P in agricultural soils has

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[19] Stimulating Sustainable Agricultural Production through Research & Innovation (SSAPRI) DAFM, 2012

[19] European Commission - Press release, Circular Economy: New Regulation to boost the use of organic and waste-based fertilisers, Brussels 17 march 2016

become a rate-limiting factor. In some jurisdictions such as the Netherlands, which hosts a very substantial pig producing industry, regulations are already in place that preclude farmers from land spreading manures. Regulations require that slurries are treated to a standard suitable for transport out of the country. Anecdotal discussions with Dutch farmers suggest they are paying up to €11 per MT for removal, drying and transport of pig slurries to horticultural sector or French tillage fields.

While farmers can utilise the nutrient value inherent in pig slurries (and are sometimes willing to pay small amounts for it) the price that slurry attracts does not cover the cost of transport. Land spread or uncovered storage of raw slurries also can cause aesthetic nuisance in terms of odours as well as environmental concerns arising from fugitive losses of ammonia to atmosphere and runoff to ground and surface waters. During late autumn months slurries have to be stored as pursuant to Ireland's NAP derogation land spreading is restricted from mid-September / mid-October through to mid / end January, depending on geographic zone. This results in a requirement for storage infrastructure and additional management costs. Development of methods that can process pig slurries for energy and nutrient recovery may also enable a reduction in pig slurry management costs.

Cattle slurries may also provide a potential source of renewable energy feedstock. Ireland feeds a dairy and beef cattle herd comprising some 6m head, while across the EU farmers raise c. 89m head. In Ireland, while there are some locations such as feedlots or cattle marts that give rise to slurry concentrations, the dairy and beef farm sectors are highly fragmented, with the average farm rearing a herd averaging < 50 head. Dairy and beef farmers employ a grass-based feeding system which means that cattle are housed outdoors in the field for most of the year, reducing the level of slurry available for collection. Using an average daily slurry output of c. 20Kg per mature head, stored over a period of 100 days suggests a potential available slurry resource of c. 12 M metric tonnes per annum, which at an average solids content of c. 10% gives rise to an annual estimated supply of slurry solids of c. 1.2M MT.

In the Irish dairy and beef cattle-rearing system the host-farm land bank provides a ready disposal route for land spread of the slurries collected during winter months when cattle are housed indoors. This restricts the slurry supply available for energy recovery and also minimises the opportunity to reduce farm costs by introducing improved methods of slurry processing. To mobilise the supply of cattle slurry as an energy resource as well as to mitigate the environmental impact arising from land spread of raw slurry, a business model is required that incentivises the farmer to make slurry available for energy recovery and improved nutrient recycling. A business model to be investigated could involve the renewable energy company processing the contents of the slurry tank via a mobile solids separation technology as a convenience to the farmer. The service could involve collection of the solids and discharge the treated liquors via pump which will avoid the need for the farmer to spread slurry. Adapting the direct farm payment system to incorporate a "greening" payment for participating in this process may provide an additional incentive by remunerating the farmer for participating as well as providing a means to cover the cost of the managed service. Recovered nutrients will have to be returned to the farmer for recycling as part of the service. The willingness of farmers to participate in this business model will have to be investigated, and the corresponding support framework adapted and introduced.

2.3. Renewable Energy Technologies to Recover Energy from De-Watered Slurry Solids

There are several technologies that can potentially be deployed for energy and nutrient recovery from slurries including Anaerobic Digestion (AD) and pyrolysis or fluidised bed combustion ATT.

AD Technology - AD generates a biogas energy carrier comprised predominantly of methane and carbon dioxide, once moisture, hydrogen sulphide and other trace elements have been removed. Biogas can be utilised in its own right to fuel boilers or specially-adapted engines, or it can be further upgraded to a biomethane standard that is interchangeable with natural gas making it suitable for injection into the gas grid or supply in pressurised containers via road haulage (i.e. the virtual grid). Biomethane is flexible, dispatchable and benefits from availability of a large, established demand for gaseous energy. AD technologies are mature, predictable and widely deployed. Europe boasts a vibrant and rapidly growing biomethane sector comprised of over 17,200[20] digesters generating an estimated 13.4 million tonnes oil equivalent (mtoe) of biomethane.[21]

Technical risks in respect of AD primarily relate to establishing a feedstock supply suitable for digestion. AD requires feedstock with a digestible volatile solids composition supplied in forms that can maintain an optimal C: N ratio. It must avoid inhibitions posed by chemical or biological contaminants as well as excessive levels of long chain fats, oils or grease (FOG). AD applications should avoid mono-digestion of feedstock comprising recalcitrant fibre or cellular structures that are difficult for microbial cultures to break down. Inappropriate feedstock recipes result in low biogas yields that have to be overcome via costly pre-treatments, high hydraulic retention times (HTR) and complex co-digestion strategies. Mono-digestion of slurry is inadvisable (as the feedstock has already passed through the livestock's enteric digestion). While the microbial cultures resident in livestock slurries will be useful to regenerate AD cultures, biogas production may be optimised if pig or cattle slurries are co-digested with a carbon-rich substrate (e.g. such as food waste, green waste or herbaceous energy crops, for example).

In the context of a slurry-to-energy system deploying filtration technology that employs ligneous biomass as a filter-aid, the recalcitrant nature of the filter aid may pose an inhibition to conventional CSTR digester designs, as it is possible that woody biomass particles may separate during the AD process causing mechanical difficulties in the digester. It may also be possible that antibiotics introduced in pig feed or the naturally-occurring anti-bacterial elements resident in wood bark may make their way into slurry solid concentrations, posing an inhibition to the AD microbiology. Optimising gas production may require introduction of pre-treatment capable of degrading the cellular structure of the filter aid. It may require methods to mitigate antibiotic compounds as well as adaptations to digester designs (e.g. a dry digester or high solids plug flow system, for example). To conclude as to the suitability of slurry solid concentrates as an AD feedstock, these factors require further investigation.

Cost of digestate disposal is a significant factor impacting AD economics. A moderate scale AD deployment that digests 25,000 MT (6,250 DMT) of feedstock may have to manage disposal of up to 60,000 MT of digestate, which could require > 2,000 agricultural scale vehicle movements. Development of technology to filter the digestate liquors in a manner that facilitates recovery and recycling of the useful nutrients in concentrated form as well as treating the water effluents to a standard suitable for immediate discharge, coupled with creation of an internal market for the fibrous digestate fertiliser, may significantly mitigate this cost. The slurry filtration technology discussed herein may potentially be adaptable for this role.

AD is generally considered sustainable, especially if a large proportion of the feedstock supply comprises wastes or residues that avoid over-reliance on feedstocks that compete with food production for land use and the associated digestate is managed in a closed system to minimise fugitive methane emissions prior to being deployed to recycle nutrients. AD is moderately energy-intensive, requiring a thermal input to maintain digester temperatures and a small electrical input to operate pumps and agitation units. Gas upgrade, compression and distribution requirements significantly increase the energy intensity. Combustion of biogas, however, is considered carbon-neutral, so in the absence of other factors that give rise to sustainability considerations, waste-to-biogas applications are likely to meet EU sustainability criteria (once introduced).

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[20] European Biogas Association (EBA Website http://www.biofuelstp.eu/biogas.html)
[21] EurObserv'ER Biogas Barometer report 2013

The current discourse in respect of slurry-based AD gives considerable emphasis to on-farm (small scale) AD deployments. Tcbb RESOURCE reviews indicate small farm-scale AD may lead to a sub-optimal unit cost of energy as farms generally do not give rise to large inherent energy demands and are sited remotely from community/industrial demand or routes to energy markets. Small farm-scale AD may find it difficult to generate economies of scale that are required to remunerate the capital cost of production infrastructure and cost of accessing distribution facilities. It may have to rely on large ongoing government subsidies to underpin economic viability. Tcbb RESOURCE economic reviews indicate that, provided appropriate methods and models can be devised to minimise cost of feedstock mobilisation, aggregation of feedstock for supply to moderate scale community digesters, sited to access existing energy demand or routes to market, may result in a lower unit-cost-of-energy.

ATT Pyrolysis – Preliminary tcbb RESOURCE investigations indicate that biomass blends comprising 50% chipped forestry brash together with 50% sewage sludge and dried to a moisture content of < 20% have a Calorific Value (CV) ranging from c. 15 - 16 MJ/Kg.[22] A similar blend comprising biomass and slurry solids would be expected to have a similar CV, as the HHV of dried slurry solids is reported to range from 17.36 – 17.85 MJ/Kg.[23] Dried to a moisture content of < 20%, these blends potentially offer an attractive and sizeable source of renewable energy feedstock suitable for thermal processing.

Pyrolysis is a thermal depolymerisation process initiated by heating feedstock in the absence of oxygen. It is an endothermic process that drives off the volatile feedstock fractions in the form of a heterogeneous synthetic gas (syngas) which can be subsequently conditioned for use as a fuel for boilers or in co-generation (PYRO-CHP). Syngas can also potentially be condensed into a liquid bio-oil, although the highly complex and heterogeneous character of the liquid may preclude cost-effective valorisation. Conversion of the biomass into a gaseous form may increase the options for commercial deployment and, if combusted, may also address concerns over particulate emissions that may arise from combustion of solid biomass fuels. Pyrolysis mineralises non-volatile feedstock fractions in the form of a biochar comprised predominantly of carbon and ash, which can potentially be used as a solid fuel or alternatively used as a soil conditioner. If used as a soil conditioner, biochar acts as a carbon sink as it is recalcitrant and resists leaching. It incorporates a level of mineralised P and K (the level of which depends on the levels of P and K bound in the organic cellular matrix of the original feedstock) which soil microbiology can release for plant uptake over time. When blended with organically sourced struvite,[24] biochar demonstrates nutritional performance equivalent to manufactured N/P/K fertilisers. The mix and characteristics of the respective pyrolysis outputs are determined by the combination of feedstock characteristics, technology design, residence time, temperature and downstream conditioning processes.

Extrapolation of data gathered from bench and pilot scale tests undertaken in the SEAI funded PYROPOWER[25] review suggests that pyrolysis of a biomass + slurry feedstock blend, dried to < 20% moisture content, would convert c. 75% of the mass balance to a raw syngas with an estimated calorific value ranging between 10 – 12 MJ/m^3 which, when conditioned to degrade tars and longer chain liquid molecules would be expected to generate a conditioned syngas of c. 8-9 MJ/m^3. The balance of the feedstock mass would be converted to a biochar expected to have a CV of c. 20 MJ/Kg.

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[22] TCBB RESOURCE, January 2016 unpublished results of bench scale investigations into HHV of WWT sludge + biomass feedstock blends

[23] Stichting Energieonderzoek Centrum Nederland: https://www.ecn.nl/phyllis2/Biomass/View/1882

[24] TCBB October 2015 results of confidential commercial field tests comparing performance of biochar + struvite against conventional N/P/K fertilisers on growth of Rye Grass, Barley and Wheat

[25] A Technical and Economic Review of Combined Heat and Power Generation from Advanced Pyrolysis of Biomass Wastes & Residues in Ireland. A n RD&D Funded by SEAI, tcbb RESOURCE; February 2018

Pyrolysis ATT is less mature than AD technology, and may require further development to advance TRLs, optimise productivity and de-risk deployment within the constraints of the current regulatory regime. Several key considerations will determine the economic viability of energy recovery via pyrolysis, including the availability of a sizeable and consistent heat demand to underpin valorisation of the thermal energy output (whether it is derived directly via syngas combustion or as one of the outputs of co-generated CHP). A second consideration will be the ability of the pyrolysis application to comply with the relevant emissions regulations. All ATT processes must comply with relevant provisions of the Industrial Emissions (IED) and/or Medium Combustion Plant (MCP) Directives, which are or will be transposed into Irish statutes. They establish, amongst other parameters, maximum Emissions Limit Values (ELV's) for release of gaseous emissions into the atmosphere. Together with other waste management and environmental legislation, they also govern release of solid residues and liquid effluents. The application of different ELV criteria, as well as the form of abatement technology to be deployed depends on whether the feedstocks are classified as "wastes" or non-wastes, as well as the source and elemental composition of the feedstock and operational parameters of the thermal process. The combination of these factors determines the types of emissions that can be expected from the process, including the potential for formation of Polycyclic Aromatic Hydrocarbons (PAH's), dioxins or other persistent organic pollutants. Feedstocks with concentrations of Chlorine at >1% by mass are of particular relevance, as the chlorine can potentially give rise to the formation of dioxins. While pyrolysis ATT can be undertaken at temperatures that potentially give rise to formation of these aromatic molecules, the pyrolysis processes avoids injection of oxygen which can act as a mitigating factor. Additionally, if the syngas is subsequently conditioned in a cracking tower + scrub unit, the temperature of the cracking application will degrade the molecular aromatic structures, oxidising PAH's to non-toxic states and disassociating the chlorine elements of dioxins so that they are dissolved into solution during the subsequent water scrub, voiding any chance of re-formation The effectiveness of this conditioning process has to be validated across a range of feedstocks with different elemental composition characteristics.

PYROPOWER prepared a techno-economic review of PYRO-CHP technology that suggests PYRO-CHP can be deployed at moderate scale to recover renewable heat, power and nutrients from dried slurry solids. PYROPOWER highlighted that PYRO-CHP technology requires feedstock with a moisture content < 20% to optimise energy recovery as well as a certain particle size and density to avoid blockage of the mechanical feed system. Identifying energetically efficient means of feedstock drying and conditioning will be key to economic performance of PYRO-CHP. Additionally, compliance with licensing and ABP regulations will require a closed system for receiving / storing the feedstock, to maintain safety of the food chain and to avoid noxious odours or other intrusions that might impact the quality of life for neighbouring residents. It identified the technology systems required a certain level of technical sophistication to ensure uninterrupted operation. These factors may require that deployment is undertaken at a minimum scale of c. 1mT per hour to remunerate capital and operating costs. It highlighted that energetic efficiency is optimised if the pyrolysis process is operated continuously while financial results are optimised if syngas can be stored and dispatched to meet peak daily heat and electricity usage profiles that vary across time slots. It highlighted that optimal storage conditions have to be identified and emissions monitoring /abatement protocols have to be agreed with relevant governance agencies to facilitate compliance with relevant IED/MCP regulations. These issues require further investigation to validate prospects for commercial deployment of slurry-based PYRO-CHP.

Fluidised Bed Combustion ATT **-** Fluidised Bed Combustion (FBC) technology is widely used as a thermal waste processing technology and may be suitable for recovery of RES H from slurry+ biomass blends. FBC heats an inert bed material such as silicates or dolomite that mixes with the feedstock to initiate combustion. It offers a high heat transfer rate between the gas and solid due to vigorous mixing of the bed material. It can accommodate feedstocks with a slightly higher moisture content (e.g. potentially up to 65% moisture) and significantly reduces feedstock volumes to bottom ash (which is separated from the bedding material and collected as a solid residue) and fly ash, comprising small particulates which are captured in an emissions control step to avoid discharge into the atmosphere. This correspondingly reduces the material management and disposal costs. Uniform temperature control enables high combustion efficiency at low temperatures with low pollutant emissions for heterogeneous, low density wastes.[26,27] Performance, however, depends on (1) design and operating conditions, (2) fuel properties, and (3) type of inert bed material used for fuel ignition.

As noted above, EU and State emissions regulations require thermal incineration applications to demonstrate compliance with ELV's that are established based on feedstock classification, feedstock characteristics and processing parameters. Emissions regulations have been recently amended to allow[28] poultry litter to be defined as an ABP that does not require extensive abatement technology when combusted in small scale (<5MWt), on-farm applications. Given this ruling, it may be possible to extend derogations to use of small scale FBC for processing other types of slurry / biomass blends.

Technical risks in respect of FBC applications include bed agglomeration that can occur when using biomass fuels with elevated/ high alkali-metal content, especially if silica/quartz sand is deployed as bed material. Feedstock comminution and conditioning may be required to ensure particle sizes and densities are suitable for supply to the mechanical feed systems. The requirement to reduce feedstock moisture is lower with FBC technology relative to pyrolysis ATT, although if low grade heat can be efficiently usefully deployed it may be desirable to reduce moisture in a manner that facilitates recovery and recycling of the resident ammonia, as well as for energetic purposes. Integration of nutrient recovery technologies still has to be optimised. FBC mineralises P and K in the ash which can potentially be utilised in its unprocessed form as a fertiliser. While concerns may arise in respect of the concentration of trace minerals in the ash, in the USA Codling et al. (2002)[29] found that trace element contents (As, Cu, Cd, Mn, Ni, Pb, and Zn) in soils amended with poultry litter ash were within the normal range of U.S. soils amended with traditional mineral fertilizer. Commercial companies such as ARS in the USA[30] and EasyMining Sweden[31] have developed technology to concentrate and remove contaminants from poultry litter. It may be possible to extend application of the conversion technology to non-poultry manures as well. Unless an ammonia recover step is incorporated into feedstock drying, N will be volatised as NO_x or N_2 during FBC combustion.

Validating techno-economic performance and regulatory compliance with particulate and gaseous ELVs may open the way for use of the FBC technology for RES-H recovery from a range of feedstocks with slightly higher moisture content such as dried slurry / biomass blends. Commercial opportunities arise for companies such as Biomass Heating Solutions Ltd. (BHSL), a County Limerick technology developer that has designed a FBC for farm-scale poultry litter. BHSL has demonstrated deployment of their technology both in boiler and steam microturbine CHP applications and this technology may be compatible[32] for use with dried de-watered slurry / biomass blends. As with pyrolysis ATT, the commercial prospects for deployment will be determined by availability of market outlets for the thermal energy outputs. Introduction of an RHI, together with extension of

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26 J.D. Martinez, T Pineda, J.P. Lopez, M. Betancur (2011) Assessment of the rice husk lean-combustion in a bubbling fluidised bed for the production of amorphous silica rich ash Energy 36 3846-3854

27 P. Ninduangdee, V.I. Kuprianov (2015) Combustion of an oil palm residue with elevated potassium content in a fluidized-bed combustor using alternative bed materials for preventing bed agglomeration. Bioresource Technology 182: 272–281

28 Decision amending EU Regulation 592/2014 on use of animal by-products as fuel in Combustion Plants, July 2014.

29 Codling, E.E., Chaney, R.L., Sherwell, J., 2002. Poultry litter ash as a potential phosphorus source for agricultural crops. J. Environ. Qual. 31, 954–961.

30 https://www.sciencedaily.com/releases/2008/03/080307081030.htm

31 https://phosphorusplatform.eu/espp-members/1579-easy-mining

32 Bujak, J.W., (2015), New insights into waste management – Meat Industry Renewable Energy 83 1174-1186.

emissions monitoring / abatement derogations to processing of ABP other than poultry litter, may open up opportunities to supply RES H to a range of rural agri-food companies or community applications.

2.4. Market Potential Arising from Improved Disposal, Renewable Energy and Nutrient Recycling

The economic value to be derived from application of the SLURRES technology arises from 2 separate value streams, including:

- Mitigation of disposal costs for feedstock owners derived from improvements relative to current methods of disposal; as well as

- The energy and nutrient value that can potentially be derived from the feedstock.

The SLURRES technology can potentially exploit market opportunities offered by processing both pig and cattle slurries, as well as processing of other slurries and sludges such as wastewater treatment sludge and AD digestates. All of these feedstock sources are available in large quantities and disposal practices are currently sub-optimal, concentrating on lowest cost disposal rather than optimal resource valorisation.

Development of the SLURRES technology can potentially improve competitiveness of the pig rearing sector. It is envisaged that SLURRES technology would be deployed as part of a slurry management service to pig farmers, separating solids for routing to renewable energy facilities and discharging treated liquors on site. Lower transport requirements driven by on-site discharge of filtered liquors would allow the service provider to charge a lesser fee for on-site processing relative to the current cost of slurry management. Preliminary estimates suggest a farmer might reduce costs by c. €3- €5 per MT.

Technology deployments at larger "fixed" processing sites may be more cost effective, as they would provide a revenue stream for the service provider based on a commercial imperative (i.e. offering a reduced cost base to the feedstock owner). Development of a mobile application would allow service providers to offer slurry processing services to small scale cattle farms. Given the current practice of slurry disposal on the host farm land bank, a contract slurry management service may not reduce the cost of slurry management for the farmer. It will however, increase convenience of slurry management as it would avoid the need for multiple field visits to spread slurry. It will also mitigate environmental impact arising from current slurry management practices. This may facilitate charging a small service fee for slurry processing which tcbb RESOURCE estimates could be in the order of €2.00 per M^3 based on anecdotal conversations with farmers (e.g. the current cost of contract removal for a 100 M^3 slurry tank is in the order of €200). If this service can be deployed in concert with an adaptation of the direct farm "greening" payment to remunerate the farmer for participating in this process, the cost to the farmer could be neutral or slightly remunerative. It the service provider is the renewable energy company, the proceeds from service fees can reduce the unit cost of energy recovered.

Domestic and commercial wastewaters represent a significant source of pressure on the water environment because of the organic, nutrient as well as hazardous substances load. With high levels of the population in EEA member countries living in urban agglomerations, a significant fraction of wastewater is collected by sewers connected to public wastewater treatment plants, which number >1,000 in Ireland and > 50,000 across the EU. In conventional municipal wastewater treatment primary (mechanical) treatment removes part of the suspended solids, while secondary (biological) treatment uses aerobic or anaerobic micro-organisms to decompose most of the organic matter and retain some of the nutrients (around 20 - 30 %). Secondary treatments result in a microbiological sludge that is considered a waste product and must be disposed of (at a cost) in accordance with increasingly strict regulations that preclude land spread on food-producing lands. Tertiary (advanced) treatment removes the organic matter even more efficiently. It generally includes phosphorus retention and in some cases nitrogen removal. Primary treatment generally removes only a small proportion of ammoniacal N, as it is dissolved in solution, whereas secondary (biological) treatment removes around 75 %.

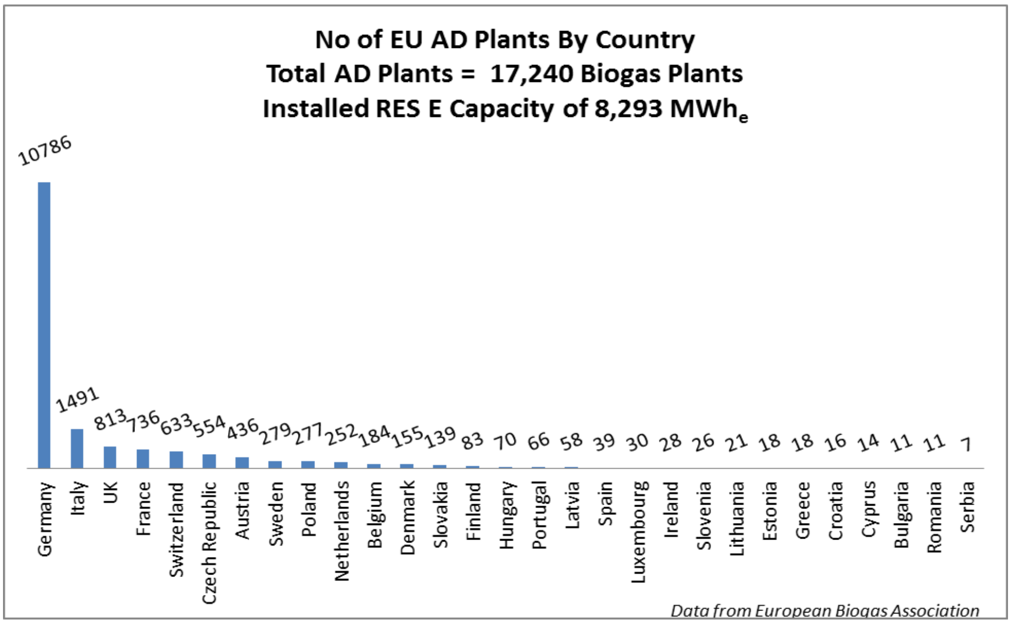
The SLURRES technology can potentially be adapted for processing municipal wastewaters, to improve separation of the primary solids that can then potentially be routed for energy recovery. This will reduce the organic loading in WWT plants, which can overcome a rate limiting factor in capacity constrained WWT plants. It may offer a means to cost-effectively expand the capacity of overloaded WWT plants, avoiding the need to increase costly construction of permanent WWT tankage. It offers a means to convert the organic loads in municipal and industrial wastewaters to energy rather than costly sludge.[33] This can reduce the cost of sewage sludge disposal, which can cost c. €60 per MT. Deployment of ATT energy technologies to recover renewable energy from separated WWT solids (directly or as a component of biomass blends) offers a means for WWT plants to generate their own energy source. In plants that deploy energy intensive aerobic treatment systems the energy cost comprises a significant element of the cost base. The high temperatures deployed in thermal ATT processes address biohazard concerns that otherwise arise in respect of land spread of sewage sludge. Thermal treatment reduces the sludge to ash, which significantly reduces volumes that require disposal.

Development of nutrient recovery technology may allow improved recovery of N for recycling in non-food applications as well as isolation of P for recycling. While nutrient recovery technologies suitable for deployment at municipal wastewater sites have to be developed (adapted) and tested, there is a large potential market outlet for this technology. Only a handful of the more than 1,000 wastewater treatment facilities in Ireland use these advanced treatment systems to recover the resource in wastewaters, reducing cost of wastewater treatment, while only c. 20% of EU WWT plants are reporting deployment of N and P recovery technologies to mitigate environmental impact. The ability to effectively process sewage sludge can potentially enable WWT operators to expand their activities, accepting septic tank sludges for co-treatment. The availability of this infrastructure will facilitate improved compliance with the recently introduced septic tank regulations, which require treatment and re-seeding of septic tanks annually. The resulting septic tank processing fees together with values arising from incremental cost reductions provides a commercial imperative that may underpin a viable marketing strategy.

AD is increasingly being deployed to recover renewable energy from a range of bio-solids such as food waste, agri-food process residues, livestock manure and energy crops. Digestate is the by-product of the AD process and is comprised of a fibrous solid component that retains between c. 33% - 50% of the original feedstock energy value (on a dry matter basis) as well as a liquor component that comprises c. 90% of the digestate mass. Digestate retains the full nutrient value of the original feedstock. They are almost exclusively disposed of by means of land spreading, which unless the AD operator has an immediately available land bank, means the transport cost of digestate disposal can become a rate limiting factor (e.g. as noted above a moderate scale AD plant may have to dispose of c. 60,000 m^3 of digestate which, if transported in 25 m^3 loads may require 2,400 vehicle movements).

[33] Low-temperature anaerobic digestion for wastewater treatment, McKeown…. O'Flaherty, Pubmed 12/2011; 23(3):444-51.

Figure 2: No of AD Plants in Europe



While AD decomposes some of the cellular structures of the feedstock which results in conversion of some of the N bound in organic cellular matrices into ammoniacal form (improving availability for plant uptake) land spread of digestate liquors generates the same environmental concerns over N loss that arises in respect of raw slurry spreading. If the AD feedstock mix includes feedstocks such as sewage sludge or land fill leachates, disposal by land spread on to agricultural lands is constrained by regulatory factors designed to maintain the integrity of food production.

Deployment of the SLURRES technology can potentially be used to process digestates, separating the solids from the liquors and recovering N from the liquors for recycling. This will allow fibrous solids to be processed for energy recovery or (for digestates sourced from non-municipal waste feedstocks) into a saleable form of organic fertiliser, while allowing the liquors to be discharged, reducing digestate transport requirements (NOTE: if municipal wastes form part of the feedstock supply then liquors may have to be routed to a WWT plant rather than discharged). Wider deployment of nutrient recovery technologies can convert inherent NH^{4+}-N to more plant-friendly nitrate forms facilitating efficient plant uptake and reducing fugitive ammonia losses from raw digestate application. The potential to reduce digestate management costs provides a commercial imperative that can underpin a viable business model.

An analysis of the universe of cost savings that could potentially be derived from technology deployment based on the material tonnages that are available across the EU28 in each of the major material sectors is as follows:

Table 1: Illustrative Market Potential of Revenues Derived from Managed Slurry Disposal Service

Material	Geographic Market	'000's Wet Tonnes P.A.	€ Estimated Fee Per Wet Tonne	Total Mkt Potential € 000's
Pig Slurry	Ireland	2,754	€3.00	€ 8,262
	UK	8,172	€3.00	€ 24,516
	EU 26 Balance	254,034	€3.00	€ 762,102
Sub Total Pig Slurry		264,960		€ 794,880
Cattle Slurry	Ireland	13,220	€2.00	€ 26,440
	UK	19,620	€2.00	€ 39,240
	EU 26 Balance	145,320	€2.00	€ 290,640
Sub Total Cattle Slurry		178,160		€ 356,320

Sewage Sludge (De watered Basis)	Ireland	580	€3.00	€ 1,740
	UK	11,370	€3.00	€ 34,110
	EU 26 Balance	78,050	€3.00	€ 234,150
Sub Total Sewage Sludge (De Watered Basis)		90,000		€ 270,000
Other Digestate	Ireland	306	€3.00	€ 918
	UK	13,000	€3.00	€ 39,000
	EU 26	208,943	€3.00	€ 626,829
Sub Total Other Digestate		222,249		€ 666,747
Total Tonnes Diverted from Land Spread		755,369	Mitigated Cost	€2,087,947

Source: TCBB RESOURCE Estimates derived from baseline data provided by Eurostat

The assumptions used to calculate these estimates are based on livestock data provided by Eurostat. The fee for processing has been estimated by tcbb RESOURCE based on discussions with stakeholders in the relevant industry taking into account estimated costs incurred pursuant to current disposal practices.

In addition to the revenues that can potentially be derived from deployment of the SLURRES technology to provide a managed service in each of the respective niche markets, additional value can potentially be derived from renewable energy generated from processing the recovered solids as well as from the value of the recovered plant nutrients. While there are different technologies available for valorisation of the renewable energy and nutrients, an estimate of the potential for energy/nutrient recovery and the corresponding market value of these activities is estimated as follows:

Table 2: Illustrative Market Potential from Renewable Energy and Recovered Nutrients

Material Market	Geo. Market	'000's DM Tonnes	CV Syngas GWh_{th}	€ 000's Value MWh_{th}	MT Mitig'd CO_2	€000'sValue Mitig'd CO_2	€000's Value N+P+K
Pig Slurry	Ireland	138	430	€ 15,062	88,092	€ 1,189	€ 1,307
	UK	409	1,277	€ 44,694	261,397	€ 3,529	€ 3,878
	EU 26	12,702	39,696	€ 1,389,360	8,125,769	€ 109,698	€ 120,542
Sub Total Pig Slurry		13,249	41,403	€ 1,449,116	8,475,258	€ 114,416	€ 125,726
Cattle Slurry	Ireland	1,057	3,305	€ 115,684	676,588	€ 9,134	€ 6,897
	UK	1,570	4,905	€ 171,689	1,004,134	€ 13,556	€ 10,236
	EU 26	11,626	36,333	€ 1,271,652	7,437,346	€ 100,404	€ 75,814
Total Cattle Slurry		14,253	44,544	€ 1,559,025	9,118,067	€ 123,094	€ 92,947
Sewage Sludge	Ireland	145	453	€ 15,861	92,762	€ 1,252	€ 458
	UK	2,842	8,884	€ 310,923	1,818,457	€ 24,549	€ 8,973
	EU 26	19,513	60,981	€ 2,134,350	12,482,901	€ 168,519	€ 61,593
Total Sewage Sludge		22,500	70,318	€ 2,461,134	14,394,120	€ 194,321	€ 71,024
AD Digestate	Ireland	25	77	€ 2,678	15,661	€ 211	€ 160
	UK	1,040	3,250	€ 113,759	665,328	€ 8,982	€ 6,782
	EU 26	16,715	52,240	€ 1,828,398	10,693,513	€ 144,362	€ 109,007
Total AD Digestate		17,780	55,567	€ 1,944,834	11,374,502	€ 153,556	€ 115,949
Total All Feedstock Markets		67,782	211,832	€ 7,414,109	43,361,948	€ 585,386	€ 405,645

Source: TCBB RESOURCE Estimates derived from baseline data provided by Eurostat

The assumptions used to prepare these illustrations are based on an average dry solids content of 5% for pig slurry, 8% for cattle slurry and AD digestates and 25% for de-watered sewage sludge. The calorific value is provided based on assumptions of an average calorific value of 15 MJ/Kg based on dry weight of feedstock inputs and assumes a mass conversion from pyrolysis technology of 75% of the dry matter mass converted to syngas. No energetic penalties have been provided for gas conditioning or other losses, and no provisions have been included in respect of the calorific value of the biochar residue. The value of the syngas energy carrier has been illustrated using €35.00 per MWh_{th} while the $CO_{2\text{-eq}}$ mitigation factor has been calculated assuming the thermal energy is used to displace natural gas. The value of the GHG displacement has been illustrated based on a CO2-eq carbon value of €13.50 per MT while the fertiliser value has been illustrated based on the assumed levels of anhydrous ammonia and phosphates estimated to be recoverable priced at current values of the fertiliser components. The values presented are illustrative, in an attempt to present the potential size of the market across the respective jurisdictions.

Commercialisation of the SLURRES technology facilitates transport of de-watered solids for renewable energy recovery at strategically located centralised sites, which tcbb RESOURCE analysis indicates results in a lower unit cost of energy relative to small-scale on-farm RES applications. Centralised energy recovery is more capital-efficient as it facilitates economies of scale and improved energy efficiency while siting of energy production infrastructure near market outlets or routes to market reduces energy distribution costs.

3. Technical Report

3.1. Introduction

It is notoriously difficult to secure efficient separation of solids, Nitrogen and Phosphorous in animal manures (particularly stored slurries) using standard mechanical separation technologies. This is due largely to the presence of a substantial portion of colloidal suspended solids that bind fine mesh screen filters. As such current mechanical filtering technologies use screens with mesh sizes above 1000 microns to avoid the build-up of impermeable filter cakes on the screens. Consequentially primary separation indices for solids, nitrogen and P are low. A previous study has demonstrated that the filter cake resistance ($\alpha_H \eta$) of pig slurry from Woodville farm in North Tipperary was 6.86 x 10^{15} mPa.s/m^2 incorporating the viscosity in the filter resistance. The value is near the upper limit of cake resistances considered permeable (10^{16} mPa.s/m^2) as expected. By adding saw dust with a lower particle size limit of 300 μm as a filter aid to the slurry at a concentration of 0.75 g/g TS, the cake resistance was reduced by more than an order of magnitude to 5.64 x 10^{14} mPa.s/m^2. The results demonstrated the feasibility of using biomass as a filter-aid to facilitate the separation of solids from animal manures and digestates using pressure-based mechanical filters. To develop improved mechanical separators for the recovery of solids, N and P from digestates and animal manures further preliminary experiments are carried out to measure the effect of different size fractions of filter aids on both the filter cake resistance and bulk permeability of slurries augmented with biodegradable filter aids. This work in undertaken with a view to developing a system for the high efficiency mechanical separation of manures and digestates that can operate continuously and be deployed at scale on farm.

The dewatering of low solids content effluent streams with environmentally unacceptable concentrations of Phosphorous and Nitrogen is an important technical challenge in green energy production, potentially affecting both the upstream and downstream materials handling and economics of anaerobic digesters and pyrolysers. For example, potential energy feed-stocks comprising animal slurries could be mobilised for green energy production in centralised anaerobic digesters or pyrolysers if their solids fraction could be sufficiently concentrated, negating the adverse transport costs associated with the logistics of delivering dilute feed-stocks to green energy production facilities. Likewise, one of the largest operating costs associated with an Anaerobic digester is disposal of the large volumes of digestate left once the volatile solids content of the feedstocks have been converted to biogas. This operating cost is similarly associated with the logistics of transporting and spreading the digestate to agricultural land for use as a fertilizer. Notwithstanding the operating costs associated with these activities, land spreading as an option for the disposal of both animal manures and anaerobic Digestates is being increasingly curtailed by European environmental legislation such as the nitrates directive and the urban waste water treatment directive. Thus, alternate strategies for the disposal of animal manures and anaerobic digestates will inevitably be needed. While much work has been done on the mechanical separation of animal manures and digestates at pilot scale using standard industrial mechanical separators including belt presses, vibratory screens and screw presses (AFBI, 2006[34]; Marcy Ford, 2002[35]; Martinez-Almela and Barrera, 2005[36]), no work has been done previously on the fundamental engineering characteristics of the filter cakes encountered in the dewatering of these materials. The fundamental relationship between the characteristics of a filter cake and its permeability to a given liquid is the Darcy equation[37] (Ripperger et al., 2000), given in equation 1.

$$\dot{V} = \frac{\Delta P . A}{L . \eta . \alpha} \qquad \text{Eq. 1}$$

Where the derivative is the volumetric flow rate, ΔP is pressure drop or applied pressure in gauge units, η is viscosity in Pa.s and α is the cake resistance at constant cake thickness L. A is the surface area of the filter. The units of α are m^{-2} but it is convenient to modify α by multiplying it by the viscosity η. The modified resistance parameter αη is conveniently reported in units of m Pa s m^{-2}.

Cake resistances can vary greatly taking on αη values ranging from very permeable at 10^8 to practically unfilterable at 10^{16} (Ripperger et al., 2000). Filter cake resistance can be measured in a number of ways. Generally, a known mass or volume of the material to be filtered is forced through a device comprising a filter of given area, at a given applied pressure (see figure 3). As the material is filtered a cake builds up and the volume of filtrate passing the filter is measured as a function of time. While under such circumstances L is not strictly constant the characteristic V(t) curve from such dynamic experiments follows the same general form, being logarithmic in the initial stages as the cake builds but settling into a linear form once a stable cake is formed. The cake thickness is measured at the end of such experiments and the steady state volumetric flow is calculated from the derivative of the linear region of the V(t) curve.

Alternatively, once a stable cake is formed on a filter a second batch of clean liquid with no solids can be filtered through a previously formed cake. As Wenping et al noted, in this static measurement the V(t) curve will be linear throughout and the steady state volumetric flow can be measured directly.[38] Measurement of cake resistance is necessary for the design and sizing of filters for a given application as it encompasses all characteristics of the cake and liquid being filtered in a single parameter. In addition, alternate strategies to improve the permeability of particularly problematic filter cakes can be tested at lab scale by testing their effect on the cake resistance parameter. One such strategy is to incorporate filter aids into the filtration system. Filter aids are solids that when added to the medium being filtered provide structural rigidity in the filter cake thus improving its resistance characteristics and its filtering performance. Materials typically used for this purpose include clays, perlite and cellulose. A biomass filter aid can be used to improve the filtering characteristics of

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35 Marcy Ford, 2002. Mechanical Solid-Liquid Separation of Livestock Manure Literature Review (Industry). Ridgetown College - University of Guelph, Ridgetown Ontario.

[36] Martinez-Almela, J., Barrera, J.M., 2005. SELCO-Ecopurin® pig slurry treatment system. Bioresour. Technol., The 10th International Conference on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture 96, 223–228. doi: 10.1016/j.bio-rtech.2004.05.017

[37] Ripperger, S., Gösele, W., Alt, C., 2000. Filtration, 1. Fundamentals, in: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA.

[38] Wenping, Li, W.L., Carl, Kaiser, C, September 19-22. Development of A Filter Cake Permeability Test Methodology. Presented at the American Filtration & Separations Society 2005 International Topical Conferences & Exposition, Ann Arbor, Michigan.

animal manures or digestates as previously demonstrated in small batch lab trials but many issues remain unresolved if an optimal continuous filtration system that can be scaled to work at useful throughputs suitable for on-farm deployment is to be developed.

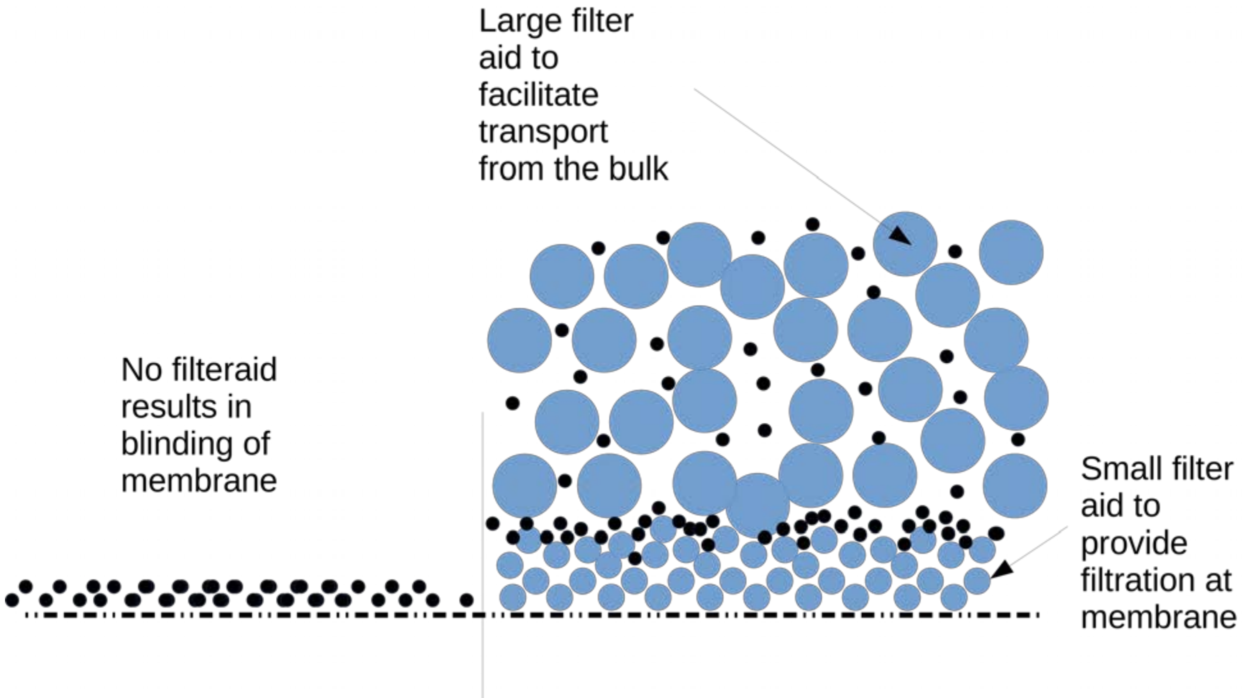


Figure 3: Schematic of Filter Aid Permeability

To this end the difference between the geometry of the lab and scale systems is significant, as at scale the slurry will be moving through larger bore pipes and liquid containing the colloidal solids must, in the first instance, move within the bulk of the slurry solids to the membrane where the colloidal solids will be separated. This is demonstrated schematically in figure 3. The motivation for conducting permeability tests with more defined particle size ranges is thus twofold:

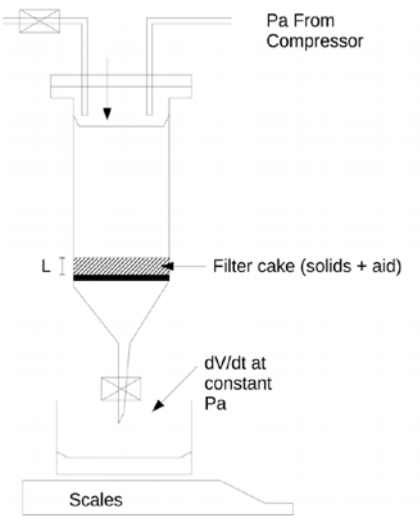
1. To determine a larger size range that facilitates high permeability of the colloidal solids through the bulk of the slurry;
2. To determine the upper limit of the smaller size range that will provide filtration.

3.2. Methodology

Cattle slurry and Pig Slurry were sourced from two separate farms in North Tipperary. The total solids (TS) and ash content were determined sequentially by mass difference by heating the slurry at 100^0 C and sintering at 550^0 C, respectively. Experiments were performed in triplicate and averaged.

To measure bulk resistance a pressurized vessel that facilitated the batch filtration of 1800 ml of test material was constructed. A schematic is presented in figure 4. The filter

Figure 4: Bench Scale Test Unit Schematic



mesh was a 2" screen gasket (125 µm) which could be easily removed from a clamp assembly for measurement of the filter cake thickness at the end of a batch filtration. The screen gasket was supported on the low-pressure side by perforated steel plate with 6mm perforations. Pressure was applied during the experimental run by means of an air compressor. To determine the filter cake resistance of a given medium with or without filter aid the V(t) curve was measured dynamically and the steady state flow rate was calculated from the linear portion of the curve. The cake thickness was measured at the end of the dynamic run. For bulk permeability tests the cattle slurry was used and for lower particle size tests the pig slurry was used. The filter aid used was waste saw dust with a D50 of 0.8mm. The saw dust was separated into several size fractions using sieves, >3.0mm, 1.0-3.0 mm, 0.5-1mm, 0.3- 0.5mm, 0.18mm-0.30mm, 0.125-0.180mm and <0.125mm. For experiments on the slurry + filter aid the filter aid was added to the slurry in the concentration 0.75g filter aid per g TS in the slurry.

3.3. Filter Aid Small-Scale Studies on Larger Particles to Maintain Bulk Permeability

Figure 5: Photograph of Bench Scale Filtration Unit

The Total Solids (TS) content of the cattle slurry used was 6.0% (± 0.35%) with an ash content of 3.1% (± 0.03%). V(t) curves were generated for the > 3mm, 1-3mm and 0.5-1mm filter-aid size fractions respectively. These materials did not filter the colloidal solids from the slurry but did facilitate removal of the larger slurry particles while maintaining the porosity and hence permeability of the full vessel contents to the liquid fraction containing the colloidal particles. The characteristic shapes are observed in the dV/dt curves and a steady state dV/dt could be measured in each case, figure 6.

The steady state throughputs were 0.263, 0.237 and 0.210 $M^3/hr/m^2$ in the >3, 1-3 and 0.5-1 mm size fractions respectively. Any of these materials are suitable as filter aids to maintain bulk permeability and the reduction in flow rate associated with the lower size fractions indicates a concomitant advantageous reduction in colloidal solids.

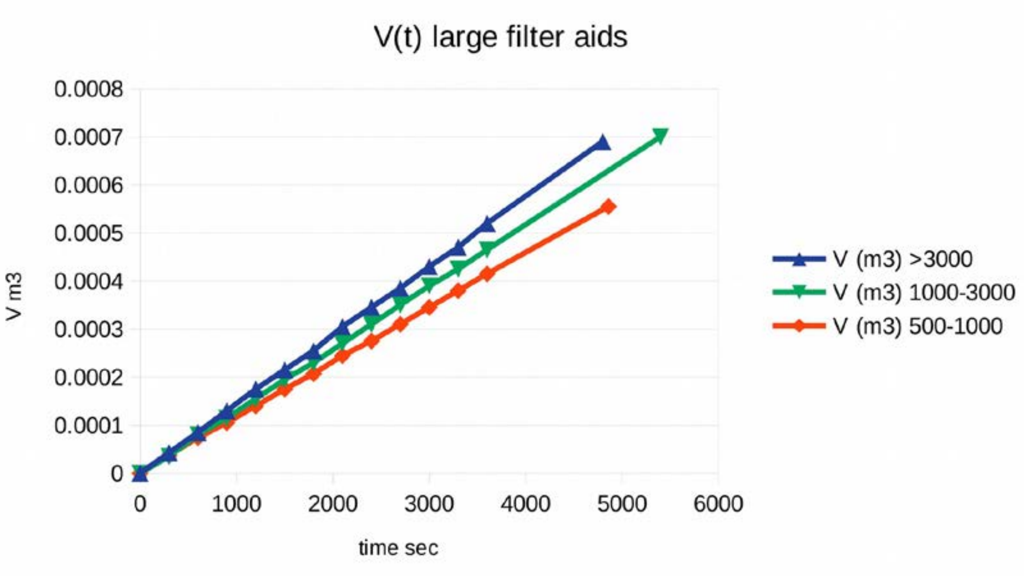


Figure 6: Large filter aid V(t) curves

3.4. Filter Aid Small Scale Studies on Smaller Particles to Provide Filtration

The Pig slurry sourced from Woodville pig farm for this study (weaning houses) had a lower solids content than that used previously (Fattening houses) with 5.37% TS of which 28% was ash. Dynamic measurements using each of the smaller particle size fractions yielded characteristic V(t) curves from which a steady state linear dV/dt could be calculated. These curves are presented in figure 7.

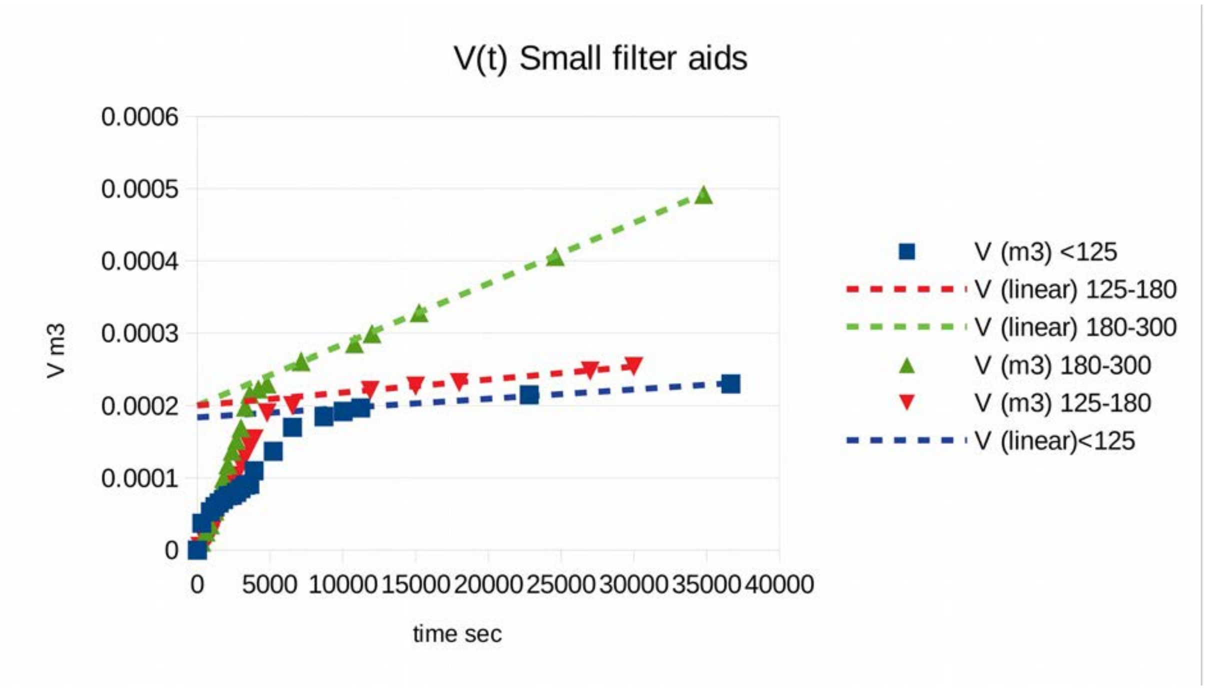


Figure 7: V(t) curves for smaller filter aids

Filter particle size in the region of 300-500 microns (i.e. 400-micron avg.) resulted in a change in terms of the filtering behaviour. This curve is presented in figure 8, with the calculated linear dV/dt at each average size presented in table 3.

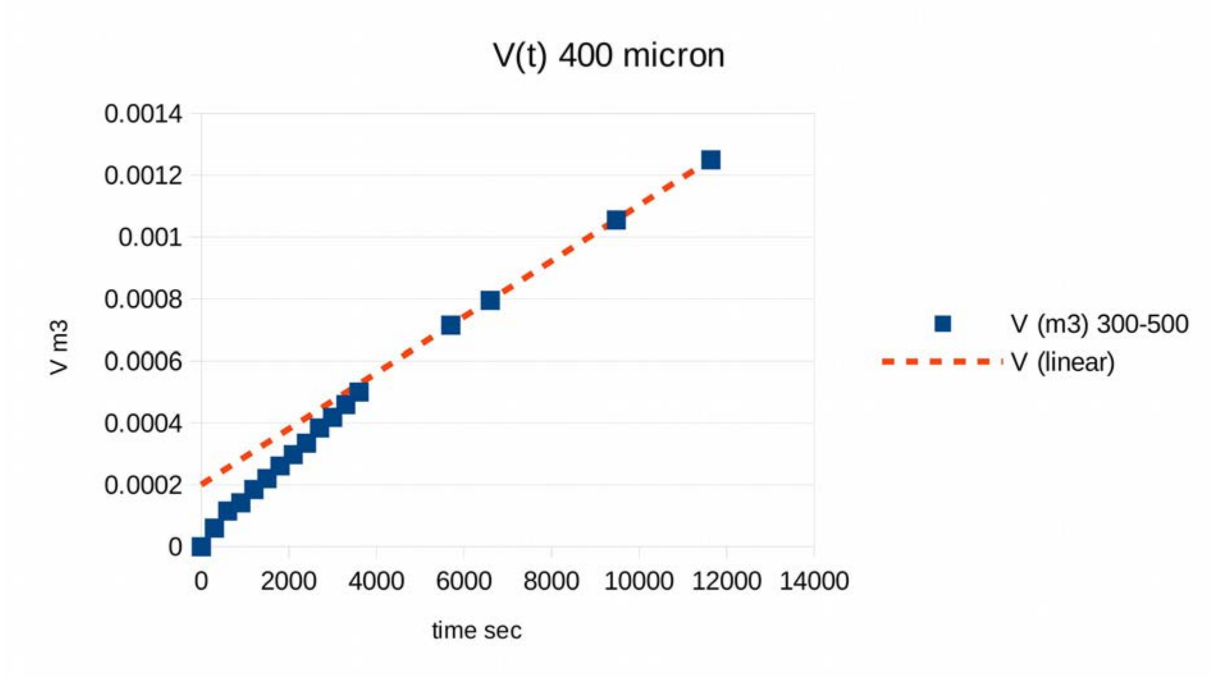


Figure 8: 300-500 Micron V(t) Curve

As expected there is a decrease in the permeability of the mix as particle size reduces, and this decrease becomes exponential once the particle size drops below 400 microns.

Particle size range	<125	125-180	300-180	300-500	500-1000	1000-3000	>3000	Prembio
Slope linear m3/sec	1.29E-09	1.800423E-09	8.41E-09	9.02E-08	1.15E-07	1.29E-07	1.43E-07	8.33E-08
Thickness m	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.05
SA m2	0.00196	0.00196	0.00196	0.00196	0.00196	0.00196	0.00196	0.00196
DelP Pa	600000	600000	600000	600000	600000	600000	600000	200000
Ave PSD µ	100	150	250	400	750	2000	4000	10
Resistance	4.57E+13	3.27E+13	7.00E+12	6.53E+11	5.14E+11	4.56E+11	4.11E+11	9.42E+10

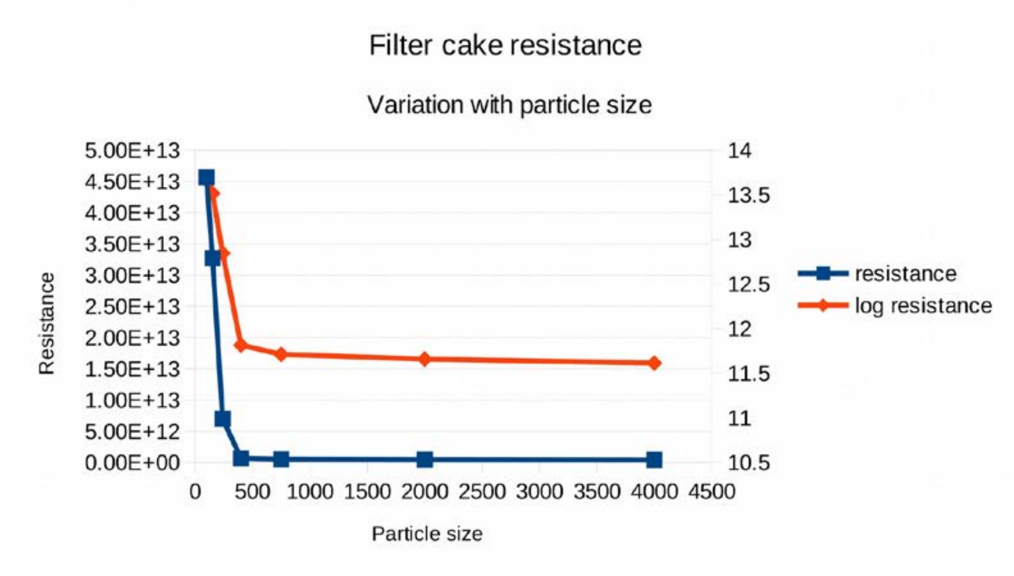
Table 3: Filter cake resistance

Taking the average of each of the particle size fractions this switch over point is clearly manifest when resistance is plotted as a function of particle size, figure 9. Below 400 microns however the relationship was determined to be exponential, described by the relation given in equation 2 for pig slurry with approximately 5% solids. D50 is the average size of the filter aid in microns.

$$\eta\alpha = 2.4066\, x\, 10^{14} \exp(-0.01468\, x\, D50) \qquad \text{Eq. 2.}$$

What is also determined by comparison with the previous study, is that the solids content of the slurry has a marked effect on the resistance parameter as expected given that viscosity is implicit.

Figure 9: Filter Cake Resistance Relative to Particle Size



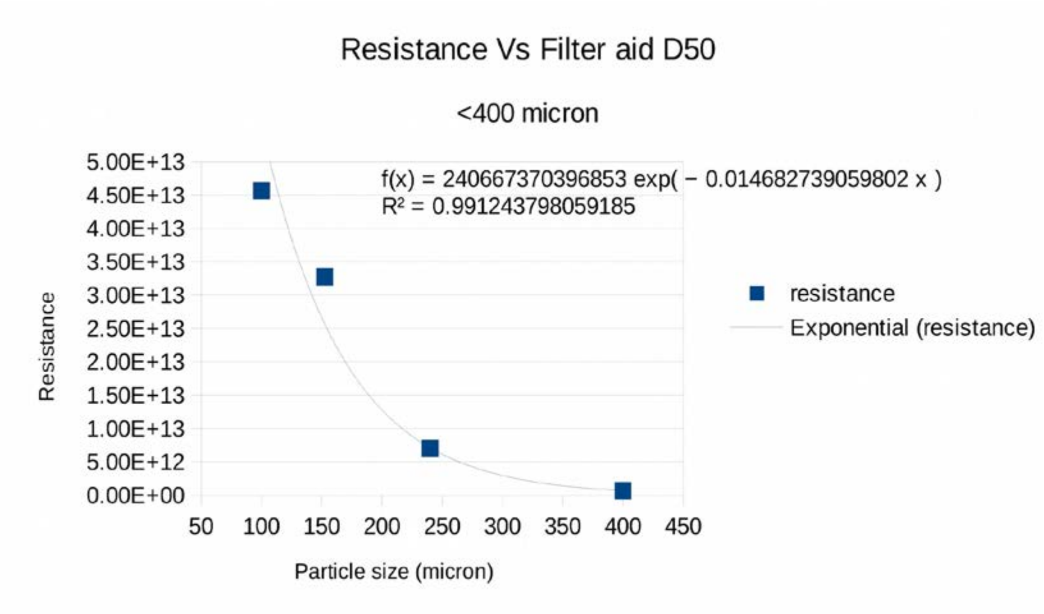


Figure 10: Resistance Vs Filter Aid

3.5. Scale-Up of the Filter Aid Concept

To test the SLURRES concept at larger scale a four-stage auger fed progressive pump was procured that has the capacity to deliver high solids materials (up to 40%) at differential pressures of 40 bar. While the engineering of a full scale, computer controlled continuous process was outside the scope of the project capital budget, a rudimentary filtration process was achieved by attaching the pump to two sintered metal filters connected in series to serve as a batch pressure filtration unit. A manual pressure gauge was included and the pump power was adjusted manually by means of an ABB inverter. For the first large batch test 45Kg of slurry (5.37% total solids) was sourced from Woodville pig farm. The slurry was added to the hopper feeder at the front of the pump with the requisite amount of filter aid, the filter aid and slurry were mixed in the hopper by the auger prior to being pumped into the sintered metal filters. As the width of the filters was 100mm considerably larger than any filter cakes encountered in the lab unit, it was decided to use the filter aid with particles sized across a broad spectrum, having both larger particles to facilitate bulk transport to the membrane and smaller particles to facilitate filtration and solids retention. This was achieved by four successive passes of a commercial saw dust (8mm) through a Farm Feed Systems mill. The system was run to squeeze the mix of filter aid and slurry into the filters under the pressure of the pump to separate a filtrate and retain the solids in the filter units.

Figure 11: Scale-Up Test Unit

Control of the system pressure was manual consisting of turning the pump on and off when the pressure reached 10-12 bar and this proved problematic. As the liquid is incompressible the pressure would spike rapidly and eventually one of the filters burst. However, 30 Kg of filtrate was collected before the filter burst and this material was forwarded to NUIG for AD trials. This material was also accessed for solids content and was found to be 0.74% solids with some 32% of this being ash. The solids separation index is calculated as the percentage of the starting solids retained in the solids fraction. In this instance:

$$1 - \frac{30\ x\ 0.0074}{45\ x 0.0537} \qquad \text{Eq. 3.}$$

The test results indicate a calculated solids separation index of 90.08%. To validate results the filter was repaired by removing the damaged section and rewelding and a second filter test was performed. Results were reproducible with the second filtrate having a solids content of 0.73%. This is exceptional given the rudimentary construct of the scale up test devices and it is expected that this number can be improved upon further with the implementation of a proper control system and the engineering of a system for the continuous removal of the solids.

3.6. Second Stage Filtration Using a Ceramic Filter Aid

The filtrate achieved by the first pass had such a low solids content as to have a viscosity close to that of water. It was decided, given this low viscosity and solids content, to test if the remaining solids could be removed by using a fine ceramic filter, 8 microns D50. Such a filter aid was available from Premier Biomaterials whom have a ceramic product of perfectly spherical dense particles engineered specifically for use in high pressure chromatography columns, these particles are engineered not to collapse under the weight of an industrial column and maintain very precise bed porosity on packing. This material was tested as a filter aid in combination with the filtrate from the scale-up run in the lab unit. The lab system was pre-loaded with a 4cm layer of the ceramic powder and the filtrate subsequently filtered through it under 2 bar pressure. The resulting V(t) curve is presented in figure 12.

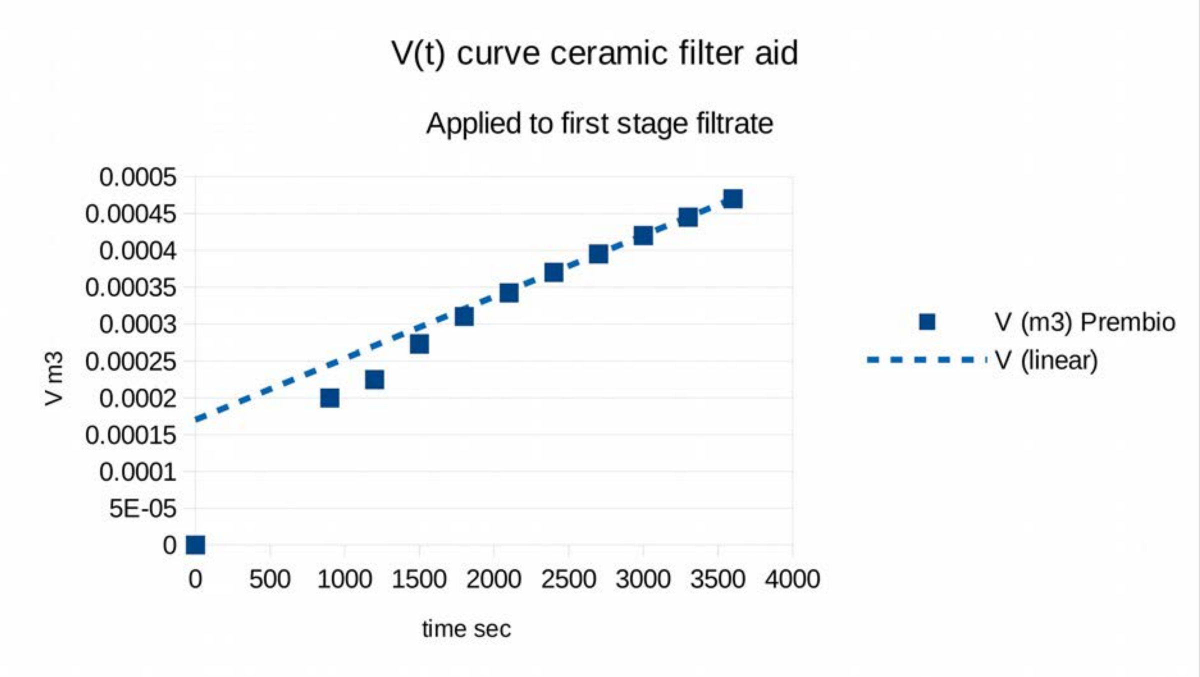


Figure 12: V(t) curve ceramic filter aid applied to the filtrate

Remarkably the resulting filtrate from this process had no detectable solids within the accuracy limits of the scales but had a yellow colour which is presumed associated with urine in the filtrate, and only visible when all colloidal solids are removed. In addition, as the solids content of the first filtrate was low the filter cake resistance was also low 9.42 x 10^{10}, and well within the limits of cake resistances considered filterable at scale. A comparison of the raw slurry, the first filtrate and the second filtrate in terms of visual appearance is presented in figure 13.

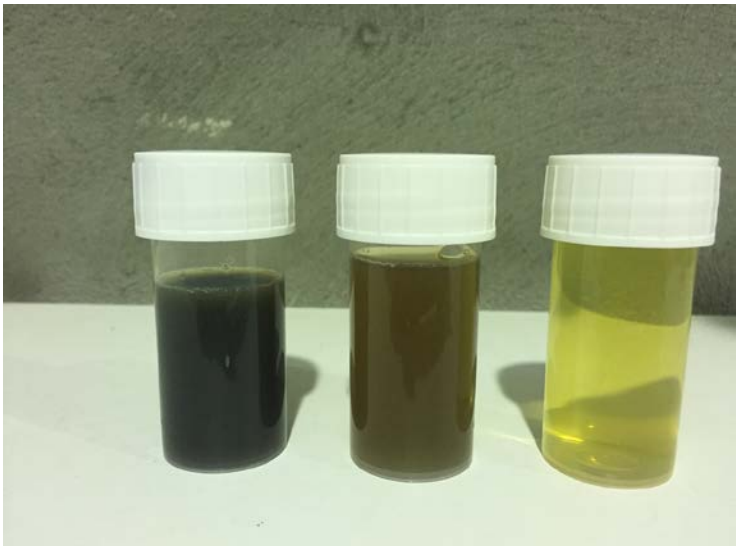


Figure 13: Photograph of Relative Solids Concentrates in Slurry, Stage 1 Filtrate and Stage 2 Filtrate

3.7. Chemical Separation Efficiency

Many previous studies have shown that a direct correlation exists between the efficiency of SS separation and the partitioning of both TN and TP. Given the high levels of solids separation achieved in the present methodology samples of the filtrates produced were analysed for TN, Ammoniacal Nitrogen and P to determine the separation indices of these key components. The separation indices achieved are listed and compared with other mechanical separation approaches in table 4.

	Separation indices %			
System	**Solids**	**TN**	**NH3**	**P**
Vibratory screen	22-43	<5	ND	<10
Belt press	22-43	<5	ND	<10
Screw auger	22-43	<5	ND	<10
Screw auger with pressure	30-50	<5	ND	<10
Centrifuge	53	21	ND	79
Centrifuge with poly+conditioner	71	34	ND	93
Present system (Biomass)	**91**	**81.5**	**77**	**97.5**
Present system (Biomass+CaP)	**100**	**84**	**81.7**	**95**

Table 4: Comparison of key separation indices

As can be seen the best separation indices achieved previously were by centrifuge with the use of both polyelectrolyte (PAM) and conditioner (alum) with 71, 34 and 93 % of solids, total N and P being partitioned to the solids fraction. The use of a fine saw dust as filter aid resulted in significant increases in the separation indices to 91, 81.5 and 97 respectively. With the addition of the CaP filter the Solids and Nitrogen indices were increased further to 100% and 84%, respectively. The use of the CaP filter has a slight negative effect on the P index most likely due to ion exchange with the filter medium itself but it is still better than any P index achieved previously at 95%.

What is particularly promising is that ammonia removal efficiencies were also high at 77 and 81.7 % in the biomass and CaP treatments respectively. This means that in absolute terms the concentration of ammonia in the filtrate can be reduced from some 2600 ppm in the raw slurry to some 730 ppm in the filtrate. The best solids separation indices achieved by commercial filter units is presented in table 4. In light of these the solid separation index achieved is remarkable given the simplicity of the approach. Given that this filtrate is also free of solids the technology provides a ready platform from which to further remediate the Nitrogen, particularly the problematic ammonia to levels that can be discharged to water courses. For example, struvite precipitation becomes a commercially viable treatment for the resulting filtrate given that the low levels of ammonia and zero solids negate the addition of large amounts of magnesium and phosphate to effect ammonia removal through precipitation.

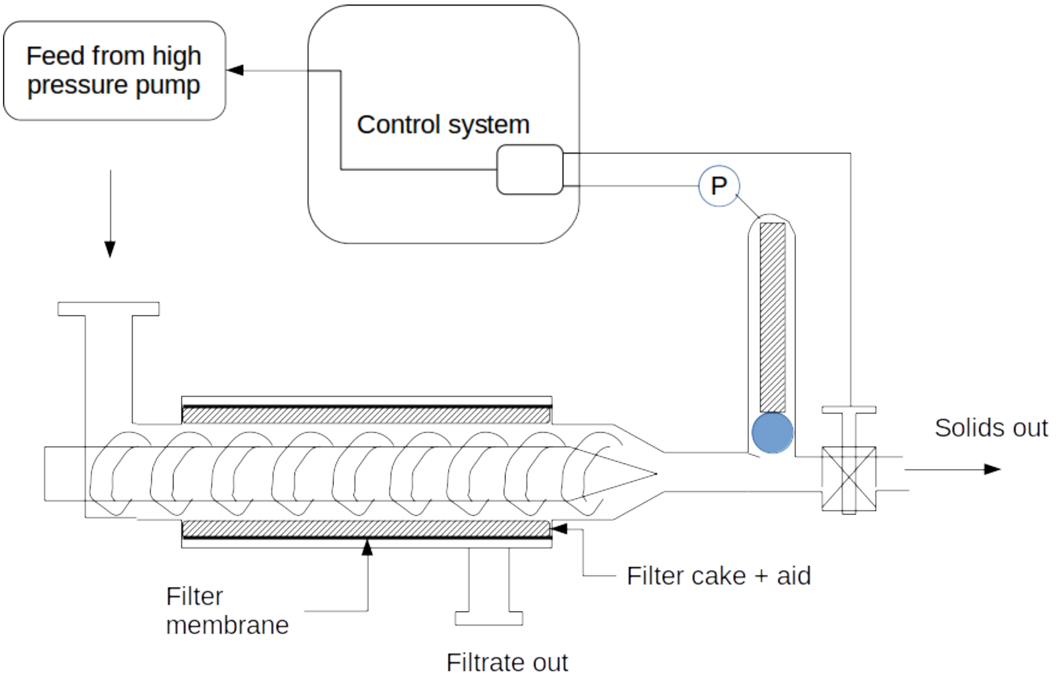
3.8. Technology and Business Model Advancement

Commercial exploitation of the SLURRES concept requires further development of the technology to engineer an automated pilot-scale and commercial unit as well as the finalisation of the business model.

Technology Development - The technology development requirements include engineering the 2-stage filtration technology into an automated continuous process that can be deployed at scale as well as development of the ammonia recovery and conversion technologies in a manner that can integrate into an end-to-end system. Development requirements include:

- *Stage 1 Pressure-Based Biomass Aided Mechanical Separation* - the stage 1 pressure-based filtration system uses a biomass filter aid combined with the solid particulates inherent in the feedstock to form a filter "cake" that operates as the filter media. This mechanical filtration technology must be engineered into an automated continuous process that can maintain the pressure required for solid-liquid separation while it injects slurry/biomass blended feedstock into the system and advances it through the mechanical separation process, concentrating the de-watered solids for extraction. The technology will require a feed mechanism to blend and supply the biomass/slurry feedstock blend as well as a vessel to house the high-pressure process that is capable of providing structural support for the sintered metal filtration cylinders. It will require integration of pressure rated entrance and exit gates together with an auger system designed to maintain the depth of the filter bed while progressively moving the solids to the exit point. It will require a computerised monitoring and control process to maintain pressures within an acceptable range as well as an expansion or overflow chamber that can be engaged in the event pressures inadvertently spike, to avoid bursting of the mechanical filter media.

Figure 14: Outline Design Schematic of Phase 1 Filtration Unit to be Coupled with N Remediation



- *Stage 2 CaP Crystal Filtration* – the stage 2 CaP crystal filtration process must also be engineered into an automated continuous process that collects and feeds the stage 1 liquor filtrates through the CaP filter unit. A pressure rated vessel is required that can house the filter media as well as facilitate easy recovery and changeout of the filter media as the residual solid particulates are extracted. The Stage 2 unit will have to be integrated with the computerise management and control system to fully automate the process.

- *Alternative 2nd Stage HRAD Technology* – to assess alternative technologies that could potentially be deployed to treat the liquor filtrates, Biomethane Potential (BMP) tests were performed on stage 1 liquor filtrates to inform how such filtrates might perform if subjected to high-rate, low temperature anaerobic digestion technology. This technology has been developed at NUIG for the purposes of treating low organic load wastewaters, and has subsequently been commercialised as an alternative to conventional nitrification-denitrification wastewater treatment. The BMP tests indicated that, while a significant proportion of the residual organic load can be removed by HRAD, the organic load was too low to contribute biomethane production at levels sufficient to consider it purely as an energy generation technology. The COD measurements from the BMP tests show a near-and medium-term reduction in COD, however then indicate that COD levels increase toward latter stages of the reaction. This is likely a result of the concentration of residual non-digestible chemical demand arising on the back of the removal of the organic load (e.g. sulphates etc). This, together with corresponding commercialisation work on HRAD technology suggests that in the Stage 1 filtrate, the residual solids levels may be too high and deployment of the HRAD technology may be better utilised as one of a several potential "tertiary polishing" technologies, that could potentially be deployed to treat the stage 2 filtrate, where much of the solid and corresponding con-digestible chemical load has been removed.

Development of Nutrient Recovery and Recycling Technology

To minimise the cost of on-farm deployment and provide the incentive for farmers to deploy the solids separation technology, complimentary nutrient recovery technology will be required to condition the filtrate liquors to a standard that can be immediately discharged, avoiding storage and transportation costs. Analysis of the filtrate liquor indicates that approximately 75% - 80% of the ammoniacal N in the original slurry is extracted with the de-watered solids while the balance is retained in the filtrate liquors. To optimise nutrient recovery, technologies are required that can recover and concentrate the ammoniacal N from both fractions, as well as a technology to convert the N into a saleable fertiliser with a quantifiable value.

In respect of the N resident in the de-watered solids, it is theorised that a large proportion is resident in the solids moisture content. If the de-watered solids are to be dried for energy recovery via thermal processing, it may be possible to adapt air stripping or steam stripping technology to recover ammoniacal N as moisture is removed from the solids fraction. In respect of N recovery from the liquor filtrates, it may be possible to adapt adsorption technology to recover the largest component of dissolved N. Hydroxyapatite (HA) crystals benefit from a useful surface chemistry that provides both positive and negative surface sites for reaction with a myriad of adsorbents. It is used extensively in pharmaceutical and food processing applications for protein separation, as well as water filtration and catalyst applications. HA is useful as a chromatography medium because its zeta potential can be changed by altering the buffering capacity of the eluent. It has been demonstrated that ammonia can be adsorbed from solution by activated carbon wherein the pH of the ammonia solution is carefully controlled to 6-6.5. It is theorised that it may be possible to generate a similar result by altering (buffering) the solution chemistry of the liquor filtrates to effect adsorption of the last n-ppm onto the HA surface, facilitating either a combined or staged removal of both solid particulates and ammonia.

If these technologies can be adapted to recover ammoniacal N in concentrated solutions, it is theorised that routing the condensates through a struvite precipitation process may facilitate N recovery in a saleable form of agricultural fertiliser. It is one of the few ammonia salts that is insoluble in aqueous solutions, which offers prospects for ammonia recovery via precipitation. The speciation chemistry however, is complex, being highly dependent on the type of magnesium and phosphate ions supplied to the reaction.as well as pH, temperature and avoidance of inhibitions caused by process media contaminants. Commercial struvite recovery technology has been developed for municipal WWT applications, while pilot-scale research projects have demonstrated that, by maintaining pH at 9-9.5, ammonia reductions of up to 98% can be achieved from agricultural liquors with starting concentrations of up to 3000ppm. Magnesium oxide and potassium phosphate are identified as sources of the balancing reagents that can achieve the stoichiometric ratio required for struvite precipitation; these materials are costly, however, and the commercial cost-effectiveness of the process will have to validated.

Further investigations will be required to determine if these technologies can be adapted to convert ammoniacal N to a commercially valuable fertiliser. Additionally, the methods for recovery and valorisation of P will have to be integrated into the respective value chain. These methods will be dependent on the processes utilised for energy recovery from the solids. If de-watered solids are utilised in AD, then the P will reside in the fibrous digestates, which can potentially be separated (and possibly dried / pelletised) for use as an organic fertiliser. If solids are dried and used as a solid fuel in thermal applications, the P will be mineralised in the residual biochar or ash. Commercial technologies are already available for valorisation of P in each of these forms, so development requirements arise only in respect of technology integration into the respective value chain.

Business Model Development - while policy drivers underpin availability of very large potential market opportunities, there are alternative processing routes for disposal of the target feedstocks, albeit costly and less sustainable. The SLURRES technology will be designed to work together in an integrated “system” (de-watered solids recovery, energy recovery as well as N and P recycling) to service slightly different market niches. Accordingly processing technologies must be developed to a specification that will facilitate integration of the component elements for the specific niche.

Additionally, deployment of the SLURRES technology is designed to compete based on processing cost. While there is a strong likelihood that the individual SLURRES technology components can be engineered to work together in an efficient end-to-end process, the proposed commercialisation activities will have to address performance optimisation, engineering and energy efficiency to validate the techno-economic viability of the integrated system. Automation of the process interactions will be required to facilitate continuous operation of the system. A low capital deployment cost and low ongoing operational cost will be key factors that underpin market demand for the SLURRES technology, and accordingly the SLURRES technology must be engineered to minimise capital deployment cost, as well as delivering a very low cost of operation. It must be designed to minimise requirement for manned supervision and minimise requirement for process reagents, materials and additives. The integration of the technology components into end-to-end systems has to be tested and optimised. The cost effectiveness of the system, as well as regulatory compliance and environmental sustainability, have to be validated.

Deployment of the separation technology to provide a managed service to small scale dairy and beef cattle farmers is likely to be dependent on adaptation of the direct farm “greening” payment to cover the cost of the managed service. This concept will have to be agreed with the DAFM, as well as tested and the respective governance framework established if it is to be introduced.

4. Conclusion

The decarbonisation of the energy mix, and compliance with related GHG mitigation and other environmental obligations, will be challenging. The commercial case for renewable energy is impacted by the current low price of oil, fragmented feedstock supplies, technology issues, sustainability concerns, public perception issues, horizontally integrated market structures and commercial frameworks that have not yet been finalised, all of which combine to preclude efficient stakeholder cooperation and constrain effective competition with well-established fossil fuels. Development of new protocols to mobilise increased supplies of low cost biomass resources to meet the increasing RES requirement will contribute to the State’s objectives, reducing unit cost of renewable energy to increase scope for RES penetration, mitigating energy-related emissions and improving resource efficiency as well as mitigating environmental impacts from intensive agriculture.

Slurry-to-energy applications offer a near term market opportunity of a scale that can make a measurable impact in respect of this transition. The business case for slurry-to-energy applications, however, is complex. Economic viability is determined equally by derivation of value from renewable energy and recovered nutrient sales as well as from environmental benefit represented by service fees underpinned either by cost savings for the feedstock owner or premiums payable to the service provider associated with processing of target RESIDUE feedstocks in an environmentally friendly manner.

A novel mechanical separation approach utilising a combination of a lignocellulosic filter aid followed by a subsequent filtration through a CaP filter bed for the treatment of pig manure has yielded significant improvements in the partitioning of key components of the slurry, achieving 100, 84, 81 and 95 % separation efficiency for Solids, Total Nitrogen, Ammoniacal Nitrogen and Phosphorous respectively. This represents a greater than two-fold increase in Nitrogen separation compared with best available commercial technologies using a simpler and more cost effective technical approach that can be deployed more readily on farm. Test results indicate almost complete separation of solid particulates as well as reduction in ammonia levels from a starting concentration of 2600 ppm in the original slurry to 730ppm in the resulting filtrate; a reduction of > five-fold on a mass basis. The de-watered solids are a suitable feedstock for energy recovery while the solids-free filtrate provides an ideal starting point for further remediation towards the ultimate goal: a filtrate effluent that is immediately dischargeable to the environment.

The results can potentially be engineered into a continuous process that addresses the competitive pressures to minimise energy production costs and optimise value recovery counterbalanced against legitimate environmental concerns that require increased mitigation of environmental impact from intensive agriculture. Commercialisation of the SLURRES technology will assist to overcome a number of the barriers constraining the economic viability of renewable energy applications, assisting to mobilise a large-scale supply of low cost feedstock in a manner that reduces the current cost or constraints currently burdening disposal of these potential feedstocks in an environmentally friendly manner. Sustainable development of a thriving RES industry, leveraging efficient use of resources, can contribute social, economic and environmental benefits, including economic growth and improved compliance with environmental obligations.

SLURRES 2017

APPENDIX 1

Review of the Biomethane Potential of Slurry Filtrate Liquors

A Research and Development Project Funded by the Sustainable Energy Authority of Ireland

ASSESSMENT OF THE BIOMETHANE POTENTIAL OF BIOMASS

NUIG Microbiology Department

Borja Khatabi Soliman Tamayo

1. Objective

The main goal in the present study has been the determination of the Biomethane Potential (BMP) of the biomass by anaerobic digestion.

2. Method

As a first step in the BMP test the Total Solid (TS) and Volatile Solid (VS) content was determined for each material in both conditions, according with the standard method (APHA 2005).

The BMP tests were carried using 500 ml bottles with a working volume of 300 ml. Each bottle was fed with 3 g of VS per litre of inoculum (anaerobic granular sludge). An inoculum to substrate ratio of 2:1 was applied.

A buffering medium was prepared using 10g/l sodium bicarbonate in distilled water. The tests were performed in an incubator to maintain constant temperature and shaking conditions at 37°C and 80 rpm. The anaerobic bottles used a 0.6 mm needle to attach a gas bag, which was used to collect the gas produced. The gas produced was analysed by gas chromatography for methane content and by positive displacement to measure volume of gas produced.

Sampling was carried out on days 0, 1, 2, 4, 7, 14, 21 and 30. The samples were analysed for soluble chemical oxygen demand (COD) analysis, Salicylate method (Ammonia NH_3-N) and percent of VS. At these sampling points biogas quality and yield are also measured. COD according to the Standing Committee of Analysts (1985).

The inoculum was acclimated for a minimum of two days, where the inoculum and 300 ml of buffer was added to each test bottle. The bottles were sealed and flushed with nitrogen for at least 2 minutes. Following this the bottles were placed in an incubator set to 37°C. After the acclimation period the substrate was added to the experimental bottles. Bottles without substrates were used as controls (controls were made in duplicate for each sampling point). At this point, the experimental trial has been started, corresponding with the "Day 0".

3. Result and discussion

- Initial Total Solid (%) = 3.85
- Initial Volatile Solids (%) = 69.10 of TS
- Initial Volatile Solids = 24.73 $gVS \cdot L^{-1}$

- Initial COD = 356.49 $mg \cdot l^{-1} \cdot gVS^{-1}$
- Highest COD (achieved at Day 4) = 989.31 $mg \cdot l^{-1} \cdot gVS^{-1}$
- Final COD = 692.88 mg·l-1·gVS-1

- Initial Ammonia = 140.56 mg·l.1·gVS^{-1}
- Highest Ammonia (achieved at Day 30) = 336.75 $mg \cdot l^{-1} \cdot gVS^{-1}$
- Final Ammonia = 336.75 $mg \cdot l^{-1} \cdot gVS^{-1}$

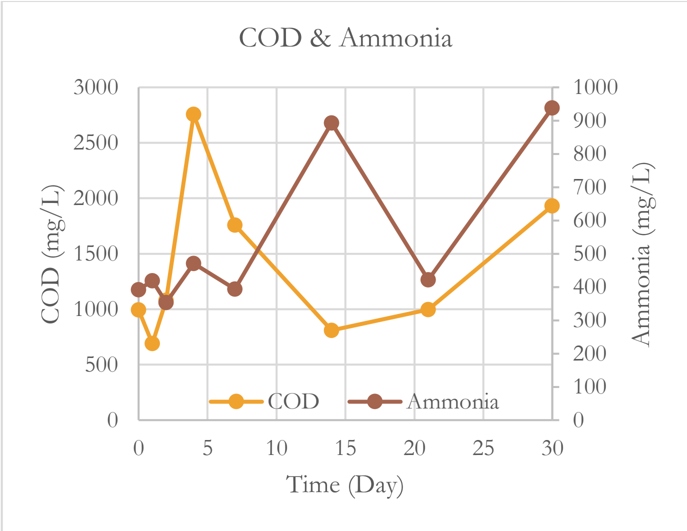


Illustration 1. Amount of COD and Ammonia (mg/L) per day tested.

- The final volume of Biomethane produced was 10.59 lCH_4/kgBiomass (50.14 lCH_4/kgVS)

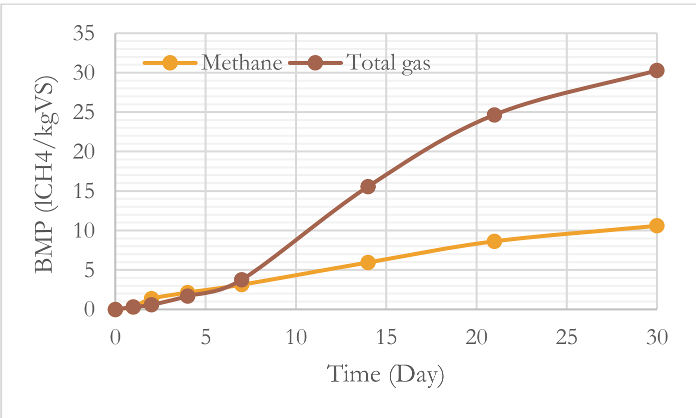


Illustration 2. Volume of Biomethane and total gas production per kg of biomass BMP test at 37°C and 80 rpm, Volume Corrected to STP: 37°C & 1 atm

For a further analysis of these results, the COD analyses and Salicylate analysis were made. The results of these appear in the illustration below:

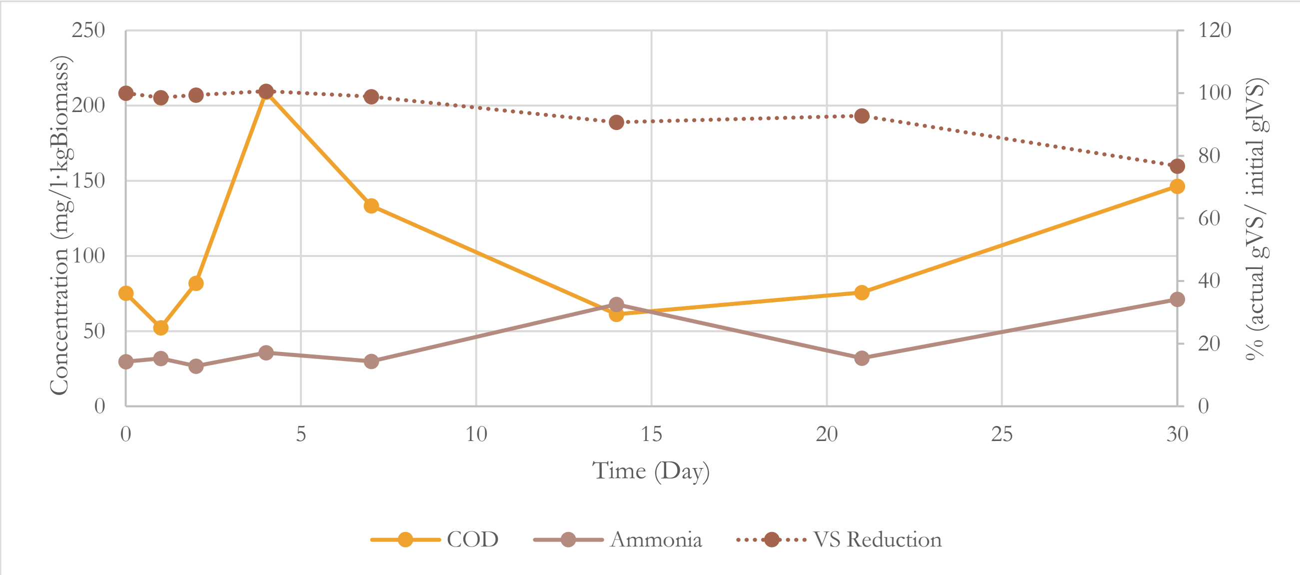


Illustration 3. COD reduction, Ammonia & VS reduction along the experiment time.

The average of methane content in total gas were between 20 – 40 % the first two weeks and around 60 % the rest of the experiment. On the other hand, the volatile solids reduction was almost of the 22% of the original, besides, the COD and NH_3-N along the experiment it was quite high.