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Bioenergy production from the co-digestion of food waste and pig manure (GreenFarm)

Key external stakeholders:
Pig producers, environmental consultants, agricultural advisors, engineers, policy makers, EPA, County Councils, SEAI, researchers.

Practical implications for stakeholders:
On-farm anaerobic co-digestion of pig manure (PM) and food waste (FW) is practiced at commercial scale across the world. However, there is a lack of information regarding how to optimise such co-digestion systems in terms of methane yields, process control, pathogen removal and digestate disposal. This project aimed to correct this. Additionally, this project, for the first time, analysed the concept in an Irish economic and regulatory context. To identify the most suitable operating conditions for the anaerobic co-digestion of PM and FW, and assess the economic feasibility of on-farm PM/FW co-digestion, experiments at laboratory scale and meso-scale were conducted..

Co-digestion of PM and FW had synergistic effects on specific methane yields (SMY). The highest SMYs were achieved at a PM/FW mixing ratio (VS basis) of 1/4. Varying digester feedstock composition from 85 %/15 % to 40 %/60 % PM/FW (volatile solids basis) did not significantly affect digestate biosafety or de-waterability. Decreasing hydraulic retention time (HRT) from 41 to 21 days did not significantly increase pathogen counts in digestate, however reducing HRT below 21 did. An economic model was developed which assessed the financial viability of on-farm biogas plants in Ireland. FW availability was the key factor in determining plant viability and due to its limited availability currently, smaller on-farm co-digestion plants were found to be most financially viable as such sites have an increased likelihood of securing sufficient FW.

Main results:

1. Co-digestion of PM and FW had synergistic effects on specific methane yields (SMY) and digestion kinetics. The highest SMYs were achieved at a PM/FW mixing ratio (VS basis) of 1/4.
2. Varying digester feedstock composition from 85 %/15 % to 40 %/60 % PM/FW (volatile solids basis) did not significantly affect digestate biosafety or de-waterability.
3. Decreasing hydraulic retention time (HRT) from 41 to 21 days did not significantly increase the concentrations of the pathogenic indicator microorganisms in digestate. However reducing HRT below 21 days had a significant negative effect on their reduction rates.
4. An economic model was developed which assessed the financial viability of on-farm biogas plants in Ireland. FW availability was the key factor in determining plant viability. Due to the currently limited amount of FW available for anaerobic digestion, smaller on-farm co-digestion plants were found to be most financially viable as such sites had an increased likelihood of securing sufficient FW.

Opportunity / Benefit:

Synergies arise from the co-digestion of FW and PM with the highest SMY achieved at a PM/FW mixing ratio (VS basis) of 1/4. HRT should be ≥21days to achieve maximum pathogen removal. The project results are readily applicable and financial viability of on-farm AD is increased when there is consistent access to FW.

Collaborating Institutions:

NUI Galway
Waterford Institute of Technology

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1. Project background:

On-farm anaerobic co-digestion of pig manure (PM) and food waste (FW) is practiced at commercial scale across the world. However, there is a lack of information regarding how to optimise such co-digestion systems in terms of methane yields, process control, pathogen removal and digestate disposal. In addition, no analysis of this concept in an Irish economic and regulatory context has been undertaken. In order to identify the most suitable operating conditions for the anaerobic co-digestion of PM and FW, evaluate the viability of using simplified mathematical tools for process simulation, and assess the economic feasibility of on-farm PM/FW co-digestion on Irish pig farms, experiments at laboratory scale and meso-scale were carried out.

2. Questions addressed by the project:

- Are there synergistic or antagonistic effects of co-digesting FW and PM on methane yields and reaction kinetics?
- Does varying the substrate composition (PM/FW mixing ratio) and digester hydraulic retention time (HRT) affect methane yields and process stability; digestate de-waterability; digestate biosafety; and microbial community dynamics?
- Does a rudimentary calibration of the International Water Association (IWA) Anaerobic Digestion Model No. 1 (ADM1) result in an accurate simulation of a PM/FW co-digestion system?
- Are on-farm PM/FW co-digestion plants financially viable in Ireland?

3. The experimental studies:

This project consisted of laboratory-scale and meso-scale experiments, and desk-based research as follows:

1. At laboratory-scale, the SMYs of PM, FW and mixtures were measured in batch experiments undertaken in 0.5 L conical flasks incubated on an orbital shaker at 37 ^{o}C. The cumulative methane generation curve from each mixture was simulated using a range of kinetic models.
2. Semi-continuous co-digestion of PM was undertaken in 10 L stainless steel jacketed continuously stirred tank reactors (CSTRs) operating at mesophilic temperatures. The effects of varying substrate mixing ratio and HRT on digester operation, digestate quality and microbiota were assessed.
3. The data generated from the batch experiments were used to calibrate a mechanistic model of the anaerobic digestion system, which was then validated using data generated from a meso-scale digester (360 L). The meso-scale digester was operated for 120 days under varying organic loading rates (OLRs) and PM and FW mixing ratios. Methane yields and system stability were monitored.
4. Data generated from laboratory- and meso-scale experiments, along with data provided by regulators, engineering firms and biogas plant operators were used to develop a financial model which assessed the viability of on-farm co-digestion of PM and FW in Ireland. Deterministic and stochastic modelling was undertaken in order to assess the financial viability under current market conditions and assess financial viability considering potential variation in market conditions in future.

4. Main results:

1. In the batch scale experiment, the synergistic effects of co-digesting FW and PM on SMYs were quantified, the effect of initial VFA concentrations on observed synergy was examined, and the suitability of several mathematical models for simulating batch anaerobic co-digestion of FW and PM assessed. The co-digestion of PM and FW had synergistic effects on SMY, substrate degradability and digestion kinetics, with the highest SMYs occurring at a PM/FW mixing ratio (VS basis) of 1/4. The highest level of synergy (22-26 % increase in SMY) was observed at a mixing ratio of 3/2.
2. The effect of undertaking PM/FW co-digestion at very low HRTs (from 21 to 10.5 days) on methane yields, digester stability, microbial communities and digester enteric indicator counts were examined. Varying digester feedstock composition from 85 %/15 % PM/FW to 40 %/60 % PM/FW (VS basis) increased SMYs but did not affect digestate biosafety or de-waterability. Decreasing HRT from 41 to 21 days (thereby increasing OLR from 1 to 3 kg VS/m^3/day) reduced the methane conversion efficiency (decreased SMY and VS removal) and improved digestate dewaterability but did not increase the enteric indicator count of the digestate. This was supported by the fact that microbial

communities were only slightly affected as PM/FW mixing ratio and HRT were varied. Decreasing HRT to 10.5 days resulted in a drop in SMYs and VMYs and a rapid increase in isobutyric acid concentrations. Reducing HRT below 21 days also compromised the ability of the anaerobic digestion system to reduce the concentrations of *Enterococcus* in digestate to acceptable levels.

3. The meso-scale reactor was operated in order to validate a mathematical model calibrated to simulate the co-digestion of PM and FW. The ADM1 model, even when calibrated in a rudimentary manner, can provide a generally accurate simulation of reactor performance. However, a low level of precision was achieved particularly when VFAs were simulated, which can limit its efficacy in predicting process stability. Therefore, a greater level of system calibration is merited when modelling systems which are highly buffered, and which treat substrates which significantly vary in chemical composition (such as PM/FW co-digestion).
4. Utilizing data generated from batch and semi-continuous experiments, as well as data collated from planned and currently operating biogas plants, an economic model was developed. This was used to assess the financial viability of on-farm biogas plants in Ireland. Despite lower operational and capital expenditure than co-digestion, mono-digestion of PM was not financially viable in Ireland. Using baseline (current market) conditions, a pig farm of 521 sows co-digesting 3000 t of FW/annum (scenario c1) was found to be financially viable with an internal rate of return (IRR) of 20 % and 126 % return on investment (RoI). Co-digesting manure from a pig farm of 2607 sows (scenario c2) and 8500 t of FW per annum was found to be financially viable with an IRR of 9 % and 11 % RoI. Larger farms (5214 sows; scenario c3) co-digesting 8500 t of FW/annum were unviable. Monte Carlo simulation revealed that, due to the high likelihood of accessing sufficient FW, net revenues from scenario c1 are least sensitive to any future changes in FW availability, gate fees, digestate disposal costs and renewable energy feed-in tariff (REFIT). Due to its potential to treat greater amounts of FW than scenario c1, whilst requiring a lower amount of FW to remain profitable relative to scenario c3, scenario c2 has the highest revenue generating potential under optimal market conditions.

5. Technology transfer:

The work conducted in this project has been successfully disseminated to stakeholders, via scientific publications, oral and poster presentations at research dissemination days, a GreenFarm Project Dissemination day and national and international conferences as well as two PhD theses.

- Irish Agricultural Research Forum (2014, 2015), Tullamore, Ireland
- 4th Annual Conference of the Ireland Chinese Association of Environment, Resources & Energy (ICAERE) (2014), Trinity College Dublin, Ireland
- Biogas Science 2014, Vienna, Austria
- Irish Pig Farmers Conference 2014, Tipperary, Ireland (2 posters)
- Environ 2015, Sligo Institute of Technology, Ireland
- 5th Annual Conference of the Ireland Chinese Association of Environment, Resources & Energy 2015, National University of Ireland, Galway
- International Water Association 14th World Congress on AD (2015), Vina Del Mar, Chile
- Teagasc Pig Farmers' Research Dissemination Day 2015, Cavan, Ireland
- Livestock Waste (2016), Galway, Ireland
- Green Farm project research dissemination workshop (2017), Grange, Co. Meath, Ireland https://www.teagasc.ie/animals/pigs/research/research-current-projects/green-farm/

Main publications:

- Dennehy, C., Lawlor, P.G., Gardiner, G.E., Jiang, Y., Shalloo, L. and Zhan, X. (2017). Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland. Applied Energy 205: 1528–1537.
- Dennehy, C., Lawlor, P.G., Gardiner, G.E., Jiang, Y., Cormican, P., McCabe, M.S. and Zhan, X. (2017). Process stability and microbial community composition in pig manure and food waste anaerobic co-digesters operated at low HRTs. Frontiers of Environmental Science and Engineering 11(3): 4.
- Dennehy, C, Lawlor, P.G., Jiang, Y., Gardiner, G,E,, Xie, S.H., Nghiem, L.D., Zhan, X.M. (2017). Greenhouse gas emissions from different pig manure management techniques: a critical analysis. Frontiers of Environmental Science & Engineering 11 (3), 11-1-11-16.

6. Compiled by: Dr. Peadar Lawlor and Dr. Conor Dennehy

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