Assessing new technologies for ammonia abatement in Northern Ireland

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*This paper examines ten comprehensive manure management systems that are considered viable in an NI context to reduce ammonia loss in raw milk production systems. Estimates of their ammonia loss, the cost of the system and the resulting abatement costs are developed to provide a comparison***.**

Background

With a growing awareness of the significant environmental costs to soil, water and air quality from excess ammonia (NH_3), there are also emerging technologies to deal with the problem. Ultimately, uptake and adoption of these systems will hinge on their economics.

Clearly, the most foolproof way to reduce ammonia loss is to reduce the amount of slurry through downsizing the cattle sector or removing quantities of slurry from the agri-food economy. In Northern Ireland (NI), this is undesirable for several reasons, not least the recognition in NI that its agri-food production, built on an extensive domestic beef and dairy agricultural supply chain, is an important source of external sales and foreign exports.

The Department for Agriculture Environment and Rural Affairs' (DAERA, 2023) preferred strategy for dealing with excess ammonia is "to drive significant levels of uptake of ammonia reduction technologies" and mention several emerging on-farm solutions that are not "currently widely utilised in NI but which have immense potential to reduce ammonia emissions and deliver on other environmental metrics such as GHGs and nutrient efficiency". To that end, several specific technologies have been identified that could be widely adopted in NI to reduce ammonia.

This paper presents a description of the systems being proposed in NI, their ammonia loss, and accompanying operational and capital costings. This is used to derive the annualised abatement costs for each system. The purpose is to inform policymakers on the likely costings and efficiency of novel technologies adoption in NI.

Methodology

Manure management systems with a potential to remove ammonia emissions were identified in what could be described as an expert-led research process. Here, a combination of scientists and policymakers identified systems that they felt were suited to current NI beef & dairy production systems. The current NI production system is characterised by relatively small farms with one hundred or so dairy cows, and so manure throughput for a one hundred cow dairy farm is assumed to be typical.

The National Ammonia Reduction Strategy Evaluation System (NARSES) was used to estimate NH_3 emissions for each system under investigation. This is a process-based tool that allows for ammonia estimation to take place accounting for technologies and practices downstream in an agricultural system (Webb and Misselbrook, 2004). Nitrogen flows were modelled, and ammonia emissions estimated from 10 different management systems for dairy slurry, to capture the partitioning of nitrogen through the various fractions that the systems produce and through the subsequent management and landspreading of these.

This method uses emission factors, as applied in NARSES at the UK inventory level, supplemented by characterisation data (e.g. manure, emissions) from relevant literature or other available sources, including directly from contractors. This overarching method is characteristic of inventories of ammonia emissions of agricultural technologies elsewhere (Misselbrook et al. (2016))

Annual ammonia emissions have been combined with annualised equivalent cost estimates to derive a cost effectiveness measure for each system; this is evidenced though a cost per kt ammonia abated of the identified system.

A systematic review of available evidence for the component parts of these systems was undertaken to derive plausible capital and operational costings for 2018, the year of the previous AFBI study (Samuel et al., 2021). This provides an overall cost for each system, under the assumption that system-wide integration confers no cost savings (e.g., the marginal cost of covered slurry stores is the same in the presence of digestate processing facilities or without).

Scenarios

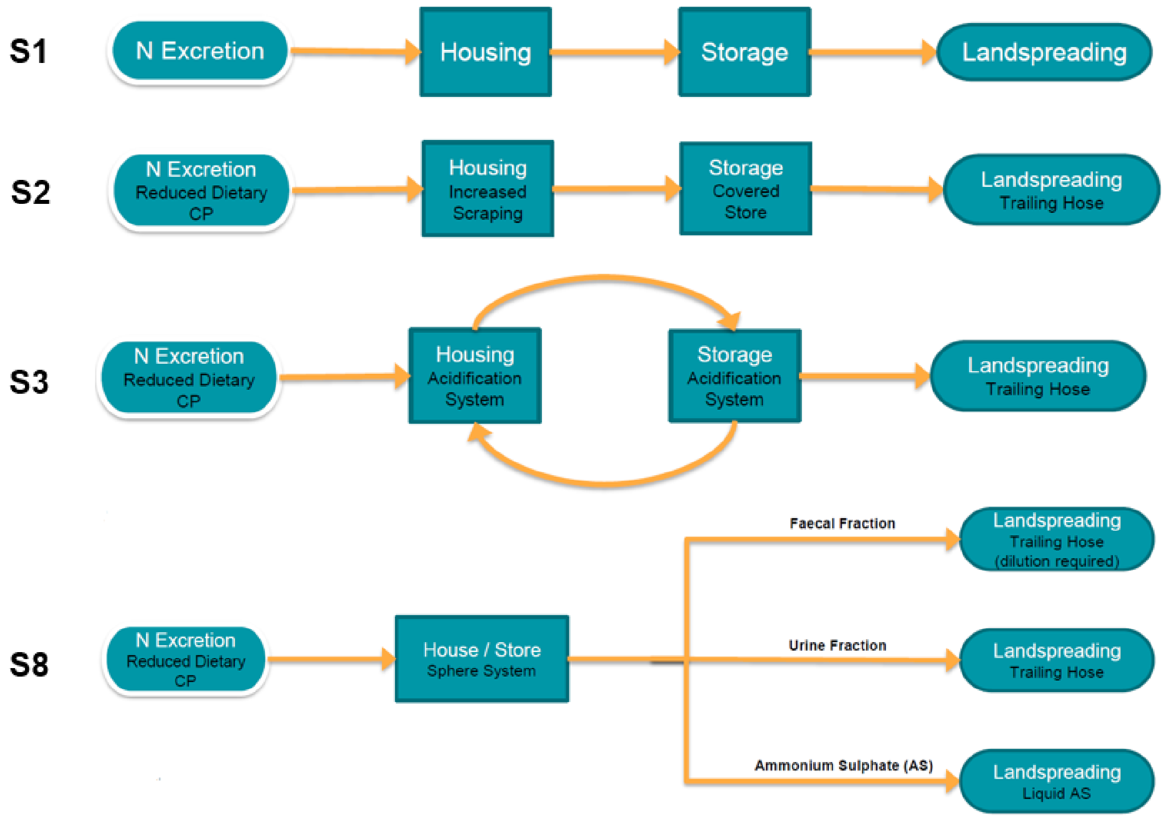
System 1 is a typical farm consisting of 100 cows managed in a fully-confined housing system. 50% of slurry is stored under house and 50% stored outdoors. It is assumed the cows collectively excrete 1,993 m^3 of slurry per annum, and all slurry is spread through splashplate. In economic terms, it is simply assumed that the cost of ammonia mitigation is zero.

System 2 adopts “on-farm” mitigations, specifically this system adds reduced crude protein diets, increased scraping frequencies in the animal house, covered stores, and trailing hose slurry landspreading. These are ubiquitous in the economic literature around both ammonia and more general Greenhouse Gas (GHG) mitigation technologies. ***System 3*** and ***System 8***, systems offer on-farm treatment of slurry and can be characterised as state-of-the-art housing systems. System 3 refers to an in-house acidification system, which is also well cited in the economic literature. The in-house slurry acidification system encompasses an outdoor store where slurry pH is monitored, and sulphuric acid is added to regulate to a target pH (5.5-6). Slurry is pumped from the store through the under-house tank and circulates back to the store. Urine and faeces that falls through the slats is incorporated into the already acidified slurry beneath.

System 8 is the Lely Sphere system and has been added primarily as a comparator for the more established acidification systems, which do not separate the slurry. The Sphere system uses a bespoke flooring system that separates urine and faeces in the house and stores these separately. There is also a bespoke sulphuric acid scrubbing system installed in the under-slat tank which creates a negative pressure in the house and scrubs NH_3 from the flooring surfaces and urine / faeces stores using an acid wash trap. This results in an ammonium sulphate (AS) solution which is a nitrogen fertiliser.

Together, systems 2,3 and 8 can be considered improved "in-house" slurry management systems, though on-farm mitigations (S2) sit separately from the more capital-intensive slurry treatment (S3, S8).

Figure 1: Improved in-house manure management regimes, (Systems 1-3,8)



The expert panel determined that an on-farm Anaerobic Digestion (AD) plant should not be considered a mitigation measure in NI. The primary logic being that AD per se is not an ammonia mitigation technology. However, a number of nutrient management systems could be applied post-AD to manage ammonia emissions from the digestate. The AD systems envisioned by the expert panel would include a much larger, profitable biorefinery, whereby slurry and digestate is transported freely (for the farmer) between the farm and plant. This system is being currently trialled in NI.

Systems 5-7,9 and ***10*** are, therefore, AD mitigation systems. These essentially offer technologies which mitigate the ammonia loss that is generated through a simple AD system, ***System 4*** is the baseline system for these scenarios, where manure is simply sent to an AD plant and returned to farm without any further processing (essentially requiring a new store). This and subsequent systems all incorporate the housing and storage mitigations from system 2, prior to an AD system.

System 5 adds on-farm digestate separation to produce solid and liquid digestate fractions which subsequently need to be stored and landspread. Systems 6,7,9 and

10 all provide further processing and storage of digestate including the generation of various post-treatment manure / nutrient fractions.

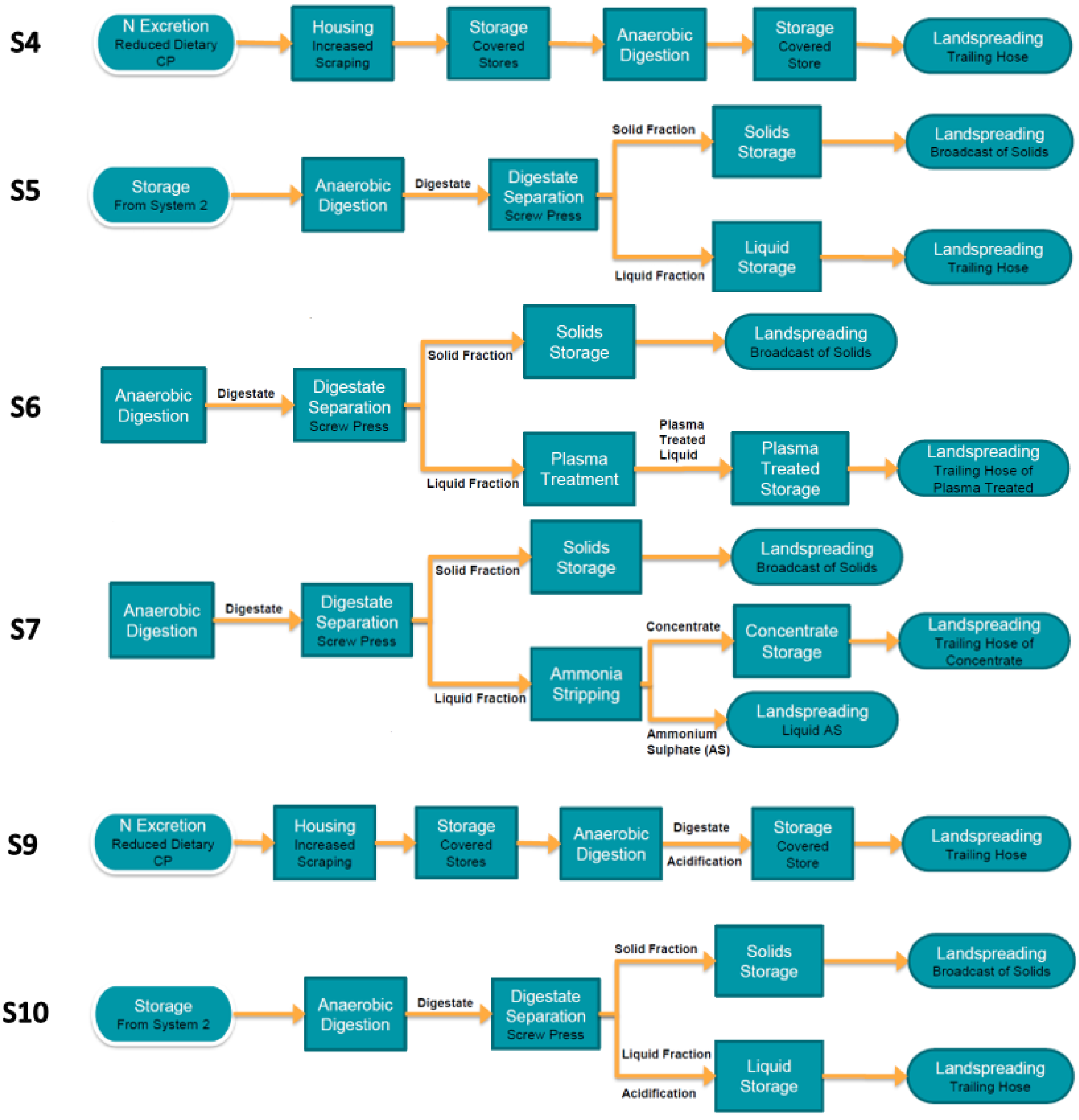
System 6 adopts an ammonia stripping process, where the digestate liquid fraction is stripped of its ammoniacal-N by sulphuric acid while under negative pressure and utilising waste heat from a Combined Heat and Power System (CHP). No NH_3 emissions are assumed from the stripping process itself, as this takes place under enclosed (negative pressure) conditions. This system produces two subsequent by-products, a digestate concentrate low in ammoniacal N but with an organic N component, and a liquid Ammonium Sulphate Solution (AS) which can be applied to land or further processed (e.g. to a granular fertiliser). The solid fraction is not processed by the ammonia stripping system.

In System 7, the digestate liquid fraction is processed by a plasma treatment system (N2 Applied). The system uses electricity and air. N_2 is fixed from the air using electricity, splitting nitrogen (N_2) and oxygen (O_2) molecules into N and O atoms forming nitric oxide. Subsequently the nitric oxide reacts with the digestate liquid fraction and lowers the pH, reducing the ammonia loss and increasing the NH_4-N available for crop use. Unlike in the ammonia stripping system which produces two subsequent by-products, the plasma treatment system produces only one, the plasma treated liquid, which will require storage prior to land application which in this case has been modelled as using trailing hose, to maintain comparability with other systems modelled.

System 9 is akin to System 4, except that digestate is acidified prior to landspreading using an in-store slurry acidification system. An in-store acidification system is an alternative to the in-house acidification system modelled in System 3. However, as slurry is acidified later in the system, emissions are not abated in the earlier stages (e.g. housing).

System 10 is similar to System 9, except for the inclusion of separation prior to acidification. In this system only the liquid fraction is acidified. The solid fraction is managed in the same way as in Systems 5, 6 and 7. Separation pre-acidification has the advantage that the liquid fraction, which retains most of the inorganic N (TAN) from which subsequent NH_3 emissions are derived, would require less acid to acidify to a target pH than it would to acidify an equivalent body of whole digestate.

Figure 2: Anaerobic Digestion manure management systems



Processing Costs of System Modules

It is assumed that every part of each system is completely modular. That is to say, the costs of, say, storage costs per m^3 of slurry in system 2 are the same as when applied in systems 6, 7, 8 and 10.

An estimate of unit costs generally measured by the annualised operational and capital costs measured as a treatment cost. This is the cost to treat cubic metre of slurry (£/m^3). These unit costs are bounded by the range of estimates found in the literature or directly from contractors. Any estimate is assumed to be an independent observation, this means that the bounds will largely be the result of macroeconomic context (i.e., more than one estimate was received outside of the base year and had to be rebased) or scaling (i.e., costs for multiple facilities are used).

System 2 (NH_3 Mitigated)

System 2 consists of on-farm mitigations and can be considered “quick-wins” in terms of NH_3 abatement. The system consists of various small-scale mitigations that are seeing increasing uptake in many manure management systems. Reduced CP diets, assumed to be cost neutral, increased in-house scraping, slurry storage covers and trailing hose landspreading.

The scraping system is taken from a supplier estimate and corroborated with press releases that advertised scraping technology. This derived an estimated cost of **£0.53/m^3-£1.50/m^3**. This range conforms to the quote underlying the work done in AFBI’s previous costing exercise (Samuel et al., 2021).

Covered stores estimates were taken from two sources. A lower bound is provided by Teagasc (2015) and an upper bound by AFBI’s previous costing. This results in an estimated cost of **£1.32/m^3-£2.44/m^3**.

Trailing hose landspreading cost estimates could not be easily derived from the literature. In the end, these were derived through expert consultations, and assumptions around how these relate to previous estimates for trailing shoe (Lalor (2008), Samuel et al. (2021)). This gives an additional cost over splashplate systems of between **£0.61 / m^3** and **£0.73 / m^3** for trailing hose.

System 3 (In-house Acidification)

System 3 is on-farm mitigation with in-house slurry acidification treatment, this will introduce major variable costs for sulphuric acid and electricity. Our latest estimates for acidification (for 2023) nearly doubled (after adjusting for inflation) the original 2018 cost estimates due to increases in costs for both inputs.

The slurry acidification system is taken from a supplier estimate, again underlying the work in Samuel et al. This was corroborated with subsequent estimates from the same supplier. It was found that the estimates do not conform to a precise scaling relationship expected, so the results of these are presented as a range; **£3.09/m^3-£5.93/m^3**.

These are in line with estimates from elsewhere (e.g., Ogunpaimo et al., 2022).

System 8 (Lely Sphere)

The Lely Sphere housing system cost estimate relies on a single contractor estimate that gives its total annualised cost of **£6.76/m^3**. This places its costing in the range of estimates provided for the in-house acidification system, which should be expected.

AD Mitigation Systems

AD plants were removed from the costing exercise, at the request of the expert panel. This is, in part, because AD processing costs are very large for small farms. This presents some conceptual problems in terms of the economic process by which a small farm with one hundred dairy cows would process digestate from an AD system.

There are some estimates for AD mitigation systems (i.e., digestate processing technologies) and emerging costings of the components of these systems are already highly variable. Several contractors simply could not provide any estimate, or indicative figures of unit costs of digestate processing (£/m^3). This, they would argue, is due the fact that these processes are sensitive to scale - the unit cost decreases as the plant size increases – and bespoke, no two plants are the same.

However, where a contractor did provide detailed cost estimates, it was for a larger system (or, "the smallest system [that they] could deliver"). This implies that these technologies are simply unable to scale down to the farm size assumed in the horizon scanning project, which is meant to present a typical NI farm.

Digestate processing is a relatively new economic process and the market for digestate is underdeveloped, though there are some cost estimates available (mostly) from Germany. Herbes et al (2020), e.g., provides detailed costings for several component parts of digestate processing, and it is naturally assumed that this would be an auxiliary part of an AD system. Commercialisation of digestate is discussed in terms of "biogas plants" or "farmers and companies operating biogas plants".

In short, digestate processing is conventionally considered to be part of an already viable AD system that could be managed by companies outside of the agricultural sector. The German literature generally assumes 2000 kW plants, and the smallest under consideration is 500 kW. The corresponding scale of the digestate processing operation would move proportionately with such plants. The capital and operational costings of ammonia stripping by Herbes et al sit in the midpoint of the range provided by Vaneeckhaute et al. (2017); **£3.96/m^3 - £7.57/m^3**. While the quote given for separation is given as somewhere between **£0.55/m^3 - £2.16/m^3**.

Plasma treatment is provided by a combination of press releases from N2 Applied that were used to advertise their plasma treatment technology facilities to UK farms with 200 and 750 dairy cows. This provides a very tentative estimate of **£1.55/m^3-£5.80/m^3**.

System 9-10 (Digestate Acidification)

A contractor estimate was given for a hypothetical in-store acidification treatment plant for mid-2023. This resulted in a very large quote, over two times the original capital and operational cost of an in-house slurry acidification plant from previous AFBI costing exercises. This is clearly a result of a combination of factors. The choice of base year, increased cost of sulphuric acid and electricity prices, all produce an estimate at £16.27/m^3 at 2023 prices. Adjusting for just these factors puts the cost of digestate acidification at **£7.37/m^3**, which brings it very close to the in-house acidification, but underlines the sensitivity of these results to broader macroeconomic environment.

The lower bound cost estimate is taken from the in-store slurry estimates derived for system 3.

Results

Figure 3 shows that the novel housing systems have drastically less ammonia loss than AD systems. This is principally due to the increased pH and ammoniacal nitrogen content of digestate, making it more predisposed to ammonia loss than raw slurry management systems such as systems 1, 2, 3 and 8.

Since the abatement technologies in system 2 are included in System 4, the excess ammonia loss arising from AD can be seen to be the difference between system 4 and system 2. This also means that AD abatement technologies (ammonia stripping, plasma treatment and acidification) aimed at reducing ammonia loss in digestate can be seen to remove all but a residual amount of the ammonia that arises from an AD system.

Figure 3: Total NH3 Loss by system

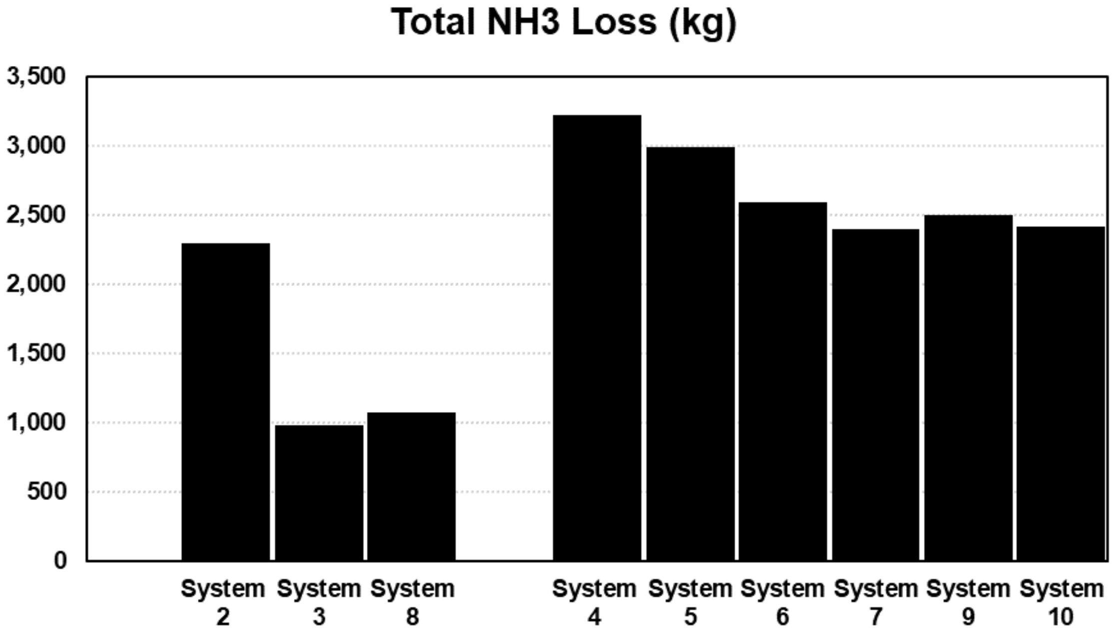


Table 1 provides the total equivalent annualised cost for each system, alongside the abatement costs. The results demonstrate that in-house systems are, by some margin, more cost-effective ammonia abatement technologies. The Lely Sphere (System 8) estimate is broadly in line with the range of contractor estimates for in-house slurry acidification (System 3).

Post-AD nutrient management systems, therefore, are both more expensive and have higher ammonia loss. It naturally follows that that will result in larger abatement costs. This is, in a large part, due to the increased storage costs required in AD systems, where digestate needs to be stored after AD processing, as well as the significant capital and running costs of the subsequent nutrient management technologies (separation , stripping, plasma treatment, acidification etc)

Table 1: Equivalent annualized costs, abatement, and abatement costs versus no mitigations

	Eq. Annualised Costs / annum (Lower)	Costs /annum (Upper)	NH3 Abated (kg) / annum	£ / NH3 kg Mitigated - Low	£ / NH3 kg Mitigated - High
System 1					
System 2	£3,900.99	£6,269.44	1309.00	£2.98	£4.79
System 3	£8,110.39	£15,571.05	2625.29	£3.09	£5.93
System 8	£14,703.60	£14,703.60	2526.93	£5.82	£5.82
System 4	£3,900.99	£6,269.44	384.93	£10.13	£16.29
System 5	£10,253.74	£15,814.18	619.29	£16.56	£25.54
System 6	£13,431.87	£25,894.42	1012.71	£13.26	£25.57
System 7	£13,178.80	£26,875.74	1210.64	£10.89	£22.20
System 9	£13,424.48	£25,822.53	1102.57	£12.18	£23.42
System 10	£17,146.46	£29,915.84	1185.14	£14.47	£25.24

Source: Various, 2018 prices

Without on-farm mitigations, systems 5-7,9 and 10 act as mitigations for system 4, and can be presented as such. Table 2 presents the abatement costs within an AD system. These technologies can broadly be described as in-store treatment facilities in that context.

Table 2: Equivalent annualized costs, abatement, and abatement costs for AD systems

	Costs / annum (Lower)	Costs /annum (Upper)	NH3 Abated (kg) / annum	£ / NH3 kg Mitigated - Low	£ / NH3 kg Mitigated - High
System 4					
System 5	£7,570.41	£10,762.40	234.36	£32.30	£45.92
System 6	£10,748.54	£20,842.63	627.79	£17.12	£33.20
System 7	£10,495.47	£21,823.96	825.71	£12.71	£26.43
System 9	£10,741.15	£20,770.75	717.64	£18.71	£35.98
System 10	£14,463.13	£24,864.06	800.21	£21.43	£37.38

Source: Various, 2018 prices

The results suggest that the abatement costs are significantly higher within an AD system. However, the total annualised equivalent costs are slightly higher than the in-house mitigation systems, where the bounds of the estimates are within the contractor estimates for the in-house systems (£8,110.39 - £15,571.05).

Discussion

The results show that in-house systems are the most effective, in terms of ammonia emissions and cost, to reduce ammonia loss in dairy farms. It is likely that on-farm mitigations may soon be mandatory and should be considered a future baseline in ammonia abatement research and development.

In turn, AD systems increase ammonia loss relative to a farm with small-scale mitigations, However, ammonia reduction technologies in post-AD digestate processing can significantly reduce emissions from AD systems, although at a higher economic cost.

Where these broad ammonia reduction conclusions are not caveat laden, the economic results are heavily caveated in comparison. The primary fact is that there are few estimates available, particularly in NI, of the cost of these developments. Here, the evidence also suggests that the viability (or payback period) will be greatly influenced by the broader economic environment (price of digestate, electricity, and other inputs into the system), as well as scale.

The overarching message is that in-house ammonia reduction systems are likely the best way to reduce ammonia loss, in terms of cost and abatement efficiency. This conclusion is likely insensitive to most economic caveats, where the same technologies applied in an AD system will be more expensive, as well as less effective at reducing overall ammonia loss. Commercialisation of AD by-products and biogas (versus by-products from in-house treatment) is perhaps the only caveat that could seriously affect parts of that overall conclusion.

Scale must be considered a problem in NI, whereby most technologies, certainly those identified by the expert panel, do not sufficiently scale down. Unit costs are scale sensitive, but NI requires technologies and systems suitable for smaller scale farms and operations. In this context, cost savings will likely be required from the technological life cycle, whereby well defined, off-the-shelf technologies can be adopted and installed quickly. Based on contractor responses, in-house systems seem to be better placed to experience cost savings from more standardised solutions.

The saving grace for AD systems are that the systems can broadly be considered to use the same technologies as the in-house slurry systems, and so technologies from in-house systems might be applied to systems with a large in-store digestate treatment component. It is likely, perhaps obviously so, that these systems will be at least as expensive as in-house systems, and difference in cost will be driven by additional infrastructure required to store the additional digestate (as well as raw slurry). It is unlikely, perhaps impossible, that an AD system will either reduce NH_3 loss more than any system that treats at source, unless slurry or its by-products are removed from a system entirely.

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