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Final Report

Evidence for Farming Initiative: Greenhouse Gas Reduction and Carbon Storage in the Pork, Potato and Protected Horticulture Sectors

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CONTENTS

1. Abstract

The AHDB is developing a What Works Centre for agriculture and horticulture called the Evidence for Farming Initiative (EFI). AHDB has developed a programme to design and develop the evidence base for this new centre. The EFI brings together fragmented knowledge and evidence on the farming industry to provide a co-ordinated central point for the delivery of quality-assured advice. The evidence-base is being developed through sector-specific rapid evidence assessments (REAs). REAs are used to provide a systematic and transparent basis to identify, critically appraise and synthesise evidence that reduces the potential for bias. The initial focus of the EFI is in investigating Net Zero practices (i.e. those that reduce greenhouse gas (GHG) emissions or sequester atmospheric carbon). After recent REAs conducted in the dairy sector and the cereals and oilseeds sector, for this current project REAs were conducted for three further sectors: pork, potato and protected horticulture. Practices that had already been captured within the previous REAs were excluded to avoid overlap.

Pork: During scoping, 17 practices were identified as having Net Zero potential, of which five were progressed to REA. Slurry cooling was found to have some indirect benefits of GHG reduction during storage, although the main target for research was its effectiveness at reducing ammonia emissions. For air scrubbing the overall GHG impact likely varies depending on the type of scrubbing system used, although all technologies were again effective at removing ammonia. Micro-anaerobic digestion shows promise to offset energy use through biogas generation, although there was a lack of case studies to be able to fully evaluate. Hydrogen electrolysis has potential future applications to reduce GHG emissions through offsetting fuel use, although there are several technical barriers to scalability. Precision feeding was found to effectively improve feed efficiency without impacting productivity, resulting in reduced GHG emissions. Overall, these practices have potential to reduce GHG emissions in the UK pig sector, although additional contextual evidence will be required to accelerate implementation.

Potatoes: Due to overlap with previously conducted REAs in the cereals and oilseeds sector, this REA focused on potato-specific cultivations and energy efficiency of potato stores, the latter of which is responsible for a significant proportion of the emissions from potato production. The approach taken for the REAs failed to identify appropriate evidence syntheses within the academic publishing sphere. Instead, attention was turned to the grey literature. Sealing air leaks and optimising insulation presented a suitable evidence base for creation of narrative summaries. Depending on the condition of the potato store, adopting these practices could significantly reduce energy use.

Protected horticulture: During scoping, 16 practices were identified as having Net Zero potential, of which five were progressed to REA. Biogas and biomass both have potential to offset fuel use in

the heated horticulture sector, although biogas has additional challenges around sourcing and price competitiveness with natural gas. North walls are a form of passive heat capture and storage which can reduce heating requirements by capturing and storing excess solar energy during the day and release it at night. Thermal screens were found to be highly effective at reducing energy use, although they are widely in use already so benefits going forward may be more around demonstrating best practice. Several aspects of glasshouse climate control have proven effective in reducing energy use, although these should be evaluated considering the whole production system. Overall, these practices have potential to reduce GHG emissions from energy use in the protected horticulture sector, although there are technical and economic challenges to implementation.

In conducting this REA, limitations in the process were identified. The focus on academic syntheses meant that for the pork and protected horticulture sectors an important body of evidence – case studies and reports in the grey literature – was not included in the assessment. This may mean that practical evidence, which may in some cases be more relevant to farmers than academic syntheses, was missed. However, the use of grey literature for the potato sector demonstrated the difficulties in finding relevant information and the uncertainty in the robustness of some data due to the lack of access to the methodological approach. The large infrastructure changes required for some of the practices identified present difficulties in conducting experimental studies of their use, limiting the data available for assessment. Case studies provide a way of capturing relevant information that can enable farms to determine the applicability of the practice to their farm.

2. Background

The UK became the first major economy in the world to pass laws to end its contribution to global warming by 2050 (CCC, 2020). In order to meet this legally binding target, all sectors of UK industry will need to reduce greenhouse gas (GHG) emissions and balance any residual GHG emissions through carbon sequestration and storage. The agriculture sector is responsible for 10% of UK GHG emissions (CCC, 2018). The NFU have set the ambitious goal for agriculture in England and Wales to reach Net Zero by 2040 (NFU, 2019). To do this will require transformational shifts and changes to current practices, as well as the development of new technologies. For this to happen, it is vital that interventions that have efficacy in reducing GHG emissions and/or sequestering carbon are identified and that farmers are provided with clear guidance on how to use them.

In the UK there is a network of 10 established What Works Centres. The centres provide guidance to their stakeholders based on available evidence. The Agricultural and Horticultural Development Board (AHDB) aims to form a centre that focuses on agriculture and horticulture. AHDB has developed a programme to design and develop the evidence base for this new centre: Evidence for Farming Initiative (EFI). The EFI brings together fragmented knowledge and evidence on the farming industry to provide a co-ordinated central point for the delivery of quality-assured advice. The EFI will provide an evidence base for agriculture and horticulture, with an initial focus on Net Zero. The evidence base is initially being developed through sector-specific rapid evidence assessments (REAs). REAs are used to provide a systematic and transparent basis to identify, critically appraise and synthesise evidence in a way that reduces the potential for bias. This approach provides a methodology that can be delivered within a relatively short period of time. It also allows for the possibility of upgrading to a more comprehensive literature review at a future stage.

For EFI, REAs have recently been produced for the cereals and oilseeds sector (Stockdale & Eory, 2020) and the dairy sector (Gill et al., 2020). Building on that body of work, this report provides REAs for Net Zero practices applicable to the pork, potato, and protected horticulture sectors. It focuses on those activities that have not already been captured by the REAs produced for other sectors.

2.1. Pork

The UK pig sector consists of around 400,000 breeding sows and gilts and 4.55m finishing pigs (DEFRA, 2020). Approximately half of UK breeding herds have 250-750 sows, with 10% below 250 sows, and the remaining 40% above 750 sows and therefore subject to permitting regulations and adherence to best available techniques (AHDB, 2019d). Unlike much of Europe, the UK has a high proportion of outdoor pig production, with 40% of sows kept outside. However, only 3-4% of finishing pigs are reared entirely outdoors, mostly for free-range or organic markets (ADAS, 2019). All other piglets are brought inside at weaning, with 60% being finished in straw-based systems and the rest on slatted concrete or plastic, as is the most common method throughout European production (ADAS, 2019).

Over the last 18 years, the global warming potential of UK pig production has been reduced by 37% (Ottosen et al., 2021). This has been achieved through productivity improvements associated with genetic gains and management changes, alongside decreased use of imported soya. Currently, over half of the GHG emissions associated with pig production are indirect emissions from the crops grown as feed. Nguyen et al. (2010) calculated the average GHG emissions to be 4.8kg CO_2e/kg pig meat (slaughter weight), based on indoor farrowing and intensive indoor finishing on slats – the predominant system in mainland Europe and a large proportion of UK production. Emissions from feed (including growing, land-use change and transport) accounted for 64% of the total, while manure management accounted for 30%. The remaining 6% was attributed to energy use – mostly for farrowing unit heating (Figure 1).

These areas are therefore the key targets for GHG emission reduction strategies. There are two approaches to reducing emissions from feed: the first is to reduce the embedded emissions from the production of that feed, and the second is to reduce the total quantity of feed required to deliver the same productive output. Practices for reducing the emissions from the production of feed were considered in the recent rapid evidence assessment for AHDB on cereals and oilseeds (Stockdale & Eory, 2020). This REA therefore focuses on practices that increase the efficiency of feed use including precision feeding, which is a form of total productive maintenance (TPM) – a holistic approach to pig production incorporating various practices. Better management of slurry, manures and energy also offer the opportunity to further decrease emissions. There are linkages between these areas with the potential to use slurry for heat (e.g. slurry cooling with heat recovery) and energy production (e.g. anaerobic digestion).

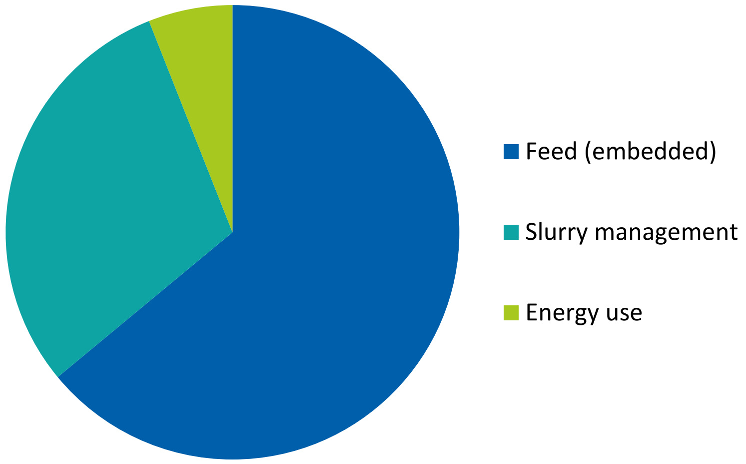

Figure 1. GHG emission sources in European pig production (indoor farrowing and indoor finishing on slats) per kg pig meat (slaughter weight). Data taken from Nguyen et al. (2010).

2.2. Potato

Approximately 5 to 6 million tonnes of potatoes are produced each year in Britain with 110,000 to 130,000 ha of planted land (AHDB, 2020). The east of England and Scotland are the main regions for potato production. Approximately two fifths are for the pre-pack market (i.e. sold to consumers) and another two fifths are for processing (i.e. used to produce crisps, chips, etc.). The remainder is for seed, fresh bags or fresh chipping.

The major sources of GHG emissions in the potato sector are from fertiliser production and application in the field, soil-related field emissions, storage of potatoes and on-farm machinery (including for soil management and planting/lifting) (Figure 2). A major component of GHG emissions in potato production is storage, which, depending on the duration, can be a significant target area for emission reduction. The breakdown of potato GHG emissions shows the large contribution of electricity, the majority of which is from storage.

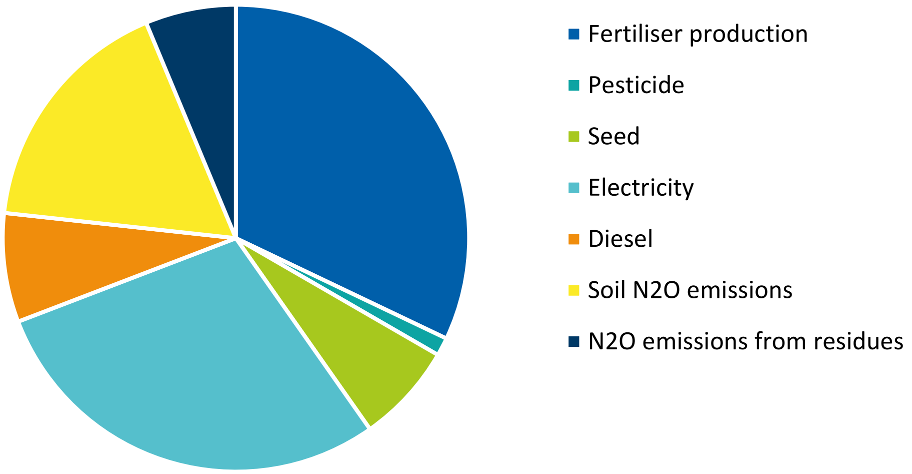

Figure 2. GHG emission sources in intensive potato production. Data taken from Wiltshire et al. (2012).

2.3. Protected horticulture

Protected horticulture covers a diverse range of systems, from simple glasshouses without lighting, heating or active ventilation, through to large-scale production in soilless substrates with supplementary lighting, CO_2 enrichment and precise temperature control. The protected vegetables sector consists of tomatoes and peppers, which are normally heated, as well as lettuce, cucumbers, and mushrooms (DEFRA, 2017). In 2019, the UK protected vegetables sector produced 269,000 tonnes of produce on 799 hectares with a value of £335m (DEFRA, 2020). The protected fruit sector in the UK refers to the production of strawberries, raspberries, blackcurrants and other soft fruit under glass, which had a value of £60m in 2018 (DEFRA, 2020). Protected ornamentals includes potted plants and cut flowers in both heated and unheated systems. The latest data for protected ornamentals is from 2015 (after which it was divided by product type), showing annual value of £321m (DEFRA, 2020).

In contrast to field horticulture and most arable crops, where nitrous oxide represents a large source of GHG emissions, carbon dioxide is the single most important GHG produced in protected horticulture. Carbon dioxide is mainly generated by the combustion of fuels (mostly natural gas) for heating with the exhaust CO_2 cleaned and used for enrichment to stimulate crop growth. Where heating is applied, it typically accounts for 90-95% of the total emissions. Torrellas et al. (2013) calculated the life-cycle GHG emissions for heated venlo tomato production under central European conditions and found average GHG emissions of 1.92 kg CO_2e/kg, with heating accounting for 95% of emissions (Figure 3A). For unheated Spanish production they reported average GHG emissions of 0.2kg CO_2/kg, with fertiliser the main source of emissions (39%), followed by those embedded in the glasshouse structure (35%), crop substrate (13%) and electricity for irrigation and cooling (9%). In heated lettuce production in the UK, Hospido et al. (2009) reported average GHG emissions of 2.62 kg CO_2e/kg, with heating accounting for 91% of emissions. In unheated UK lettuce production, they found average GHG emissions of 0.24 kg CO_2e/kg, with postharvest cooling the main source of emissions (36%), followed by transport to retail (24%), supplemental lighting (12%) and crop propagation (11%).

Heated glasshouses make up a large proportion of the UK industry, including most tomato and pepper production, and in these systems the main focus of emission reduction strategies is to reduce energy use. This includes the use of alternative renewable fuels such as biomass and biogas, as well as other practices to reduce heat requirements such as thermal energy storage and thermal screens, which can also be applied to unheated glasshouses to improve productivity. Managing the internal glasshouse climate to ensure optimal crop growth is a common theme within several practices across the protected horticulture sector.

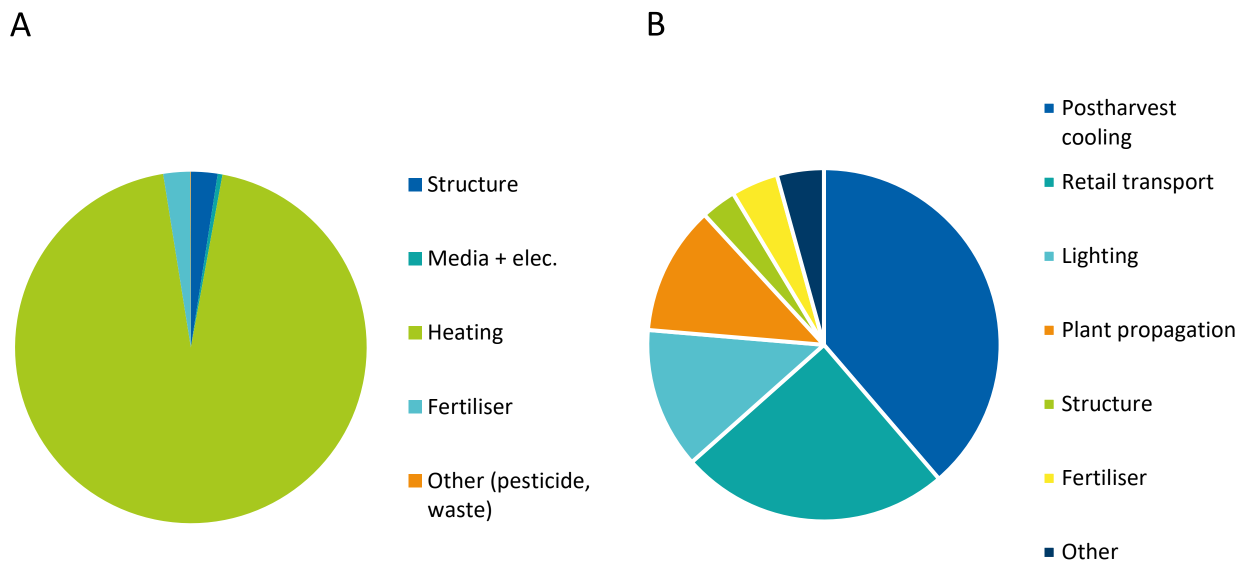

Figure 3. GHG emission sources in European heated venlo tomato production (a) and unheated British glasshouse lettuce production (b). Data taken from Torrellas et al., 2013; Hospido et al., 2009.

3. Project Aims and Objectives

3.1. Aim

The aim of this project is to conduct rapid evidence assessments (REAs) for Net Zero carbon practices applicable to the pork, potato, and protected horticulture sectors to provide AHDB with an overall picture of the evidence landscape.

3.2. Objectives

The research has several core objectives:

- To provide REAs on practices that reduce GHG emissions and/or increase carbon storage and develop proxies for quality of the evidence
- To translate REAs into narrative summaries for each practice that can be presented to farmers and growers through EFI
- To outline existing evidence syntheses and the nature of these syntheses, as well as to identify gaps in the evidence-base as a focus for further research priorities
- To outline where there are future data developments and technologies that may give greater insights than current research and data methods may facilitate
- To provide feedback on AHDB's 'organising framework for evidence' and 'generation and application of evidence standards' working drafts

3.3. Report structure

The structure of the report is as follows:

- The next section (**section 4**) presents the methodology used for conducting the REAs.
- **Sections 5**, **6** and **7** present the results for the pork, potato and protected horticulture sectors, respectively. These consist of:
  - Scoping exercise – The outcome of the scoping process for identifying the potential Net Zero practices.
  - Literature search (for the potato sector only) – This is a discussion of the grey literature used in the critical review and narrative summaries.
  - Critical review – The selected practices are discussed here. Those that were found to have sufficient evidence for Net Zero are presented as narrative summaries (in **Appendices 10.2-10.4**), with a clear description of the practice and its evidence base. The practices with insufficient evidence to progress to REA are briefly discussed, with recommendations for future work where applicable.
- **Section 8** is a discussion on the practices that were identified and an evaluation of the process by which they were assessed.
- **Section 9** contains the references cited in this report.

- **Section 10** contains the appendices
  - **Appendix 10.1** provides the Evidence for Farming Initiative Draft Standards to which the practices where scored.
  - **Appendices 10.2**, **10.3** and **10.4** contain the narrative summaries for the pork, potato and protected horticulture sectors, respectively.

4. Rapid Evidence Assessment Methodology

A rapid evidence assessment (REA) is a commonly used approach to review an evidence base where time or resource constraints are prevalent. Whilst a REA applies the same methodological steps as a more comprehensive systematic literature review, a REA makes concessions in relation to the breadth (e.g. only including specific research designs), depth (e.g. only extracting a limited amount of key data) and comprehensiveness of the search (e.g. only consulting a limited number of databases). This enables REAs to be delivered within a relatively short period of time, whilst also providing a robust and systematic approach to provide an evidence summary that can inform practice (Collins et al., 2015). The overarching methodology for the REA is the same for each sector, however individual sector-specific differences are considered and addressed accordingly.

Due to the time constraints of this project, the intention was that the main body of evidence being considered for these REAs would be limited to syntheses, such as systematic and descriptive reviews, rather than primary research studies. However, due to limited availability of these research syntheses for the potato sector, the scope was widened to include grey literature. The process for the REAs is set out below.

Identify target outcomes and practices

For each sector, a scoping exercise was conducted to identify examples of farming methods and outputs that can reduce GHG emissions or increase carbon storage (hereby referred to as "practices"). A list was compiled through a search of the academic and grey literature (i.e. research outside of the traditional academic publishing sphere) and supplemented with practices identified by technical experts from the relevant sectors. The practices were grouped according to overall outcome and those considered to have the greatest potential as Net Zero practices were identified. For each of these, a primary research question was determined to guide subsequent work in the format of: "Does [practice] reduce GHG emissions/enhance carbon sequestration in [sector]?"

Define search terms and databases

Using the primary research question, search terms were created for each practice, based on the systematic search approach outlined by James et al. (2016). Search terms were created using the key words from the practice and the anticipated outcome e.g. "GHG emissions" or "fuel use". Searches were tested in Google Scholar and refined until the resulting paper titles were relevant to the research question according to the Population, Intervention, Control, Outcome (PICO) methodology (Richardson et al., 1995). The final search terms were recorded for reproducibility and the top 10 results were copied into a literature database. The search terms were then run on ScienceDirect and any additional papers in the top 10 results were included in the database. This formal approach was also supplemented with individual research papers and ad hoc searches of grey literature, as well as the inclusion of literature that was already known to the project team.

Screening and selection of evidence

All evidence was collated into a database (e.g. author, year, title, abstract etc.) and then the titles and abstracts were screened based on the relevance to the research question and assigned one of 3 grades – green (directly relevant to the practice and outcome), yellow (indirectly relevant to the practice and outcome) or red (not relevant to the practice and outcome). Each paper was screened again by a second reviewer to minimise bias and reduce the risk of excluding relevant papers. The papers which received at least one green grade were filtered and progressed to the appraisal stage. After green papers were appraised, yellow papers were reviewed more thoroughly and those that met the inclusion criteria were forwarded to the appraisal stage.

Appraisal of evidence

The selected evidence was critically evaluated based on the robustness of its methodology and the relevance of its context to the research question. Combining these ratings provided an overall assessment of the weight to be given to each item for the evidence synthesis. This process highlighted the strength of evidence within individual publications. Any papers which were deemed irrelevant to the research question or of very poor quality were excluded from further analysis. The papers were also scored on their conclusions regarding the relevant practice, including its effectiveness, cost, and speed of implementation. Combined with the information on the quality of the evidence, this provided a measure of how practical and effective the practice is, and how strongly the evidence supports that claim. Where there was sufficient industry/academic research and published material, the evidence was progressed to narrative summaries. Where the evidence base was limited or obsolete, but the evidence that was available suggests that the practice has potential, these were identified as target areas for future research.

Translation of REAs into narrative summaries

The REA process provides a synthesis of the evidence-base for each practice assessed within the relevant sector. The technical and academic information was then translated into narrative summaries aimed at helping farmers understand the practice and how to implement it in a practical sense. These include a descriptive impact summary, a summary of the weighted scores for evidence quality and support for each practice, as well as descriptive summaries of what the practice is, how effective it is, which contexts it works in, an estimated cost of implementation, what best practice looks like, the strength of the evidence base, and links to further information.

5. Pork

5.1. Scoping exercise

The initial scoping exercise aimed to find broad reviews of Net Zero practices in the UK pig sector. While feed accounts for most emissions in pig production, these embedded emissions are largely beyond the control of individual farmers and operators (Nguyen et al., 2010). Manure management is typically the second largest source of emissions and is widely discussed in the GHG mitigation literature.

Philippe & Nicks (2015) provide a detailed comprehensive review of the sources and types of GHG emissions from pig housing. They breakdown emissions by physiological stage, quoting emission factors for gestating sows, farrowing sows, weaned piglets, and fattening pigs, from a range of different countries. They discuss the impact of housing design, the merits of slatted systems versus bedded systems, and the range of manure management systems that are available and their respective implications for GHG emissions. The authors provide a comprehensive review of the mitigation techniques that can be applied to each type of production system, summarising knowledge-to-date on effectiveness in reducing GHG emissions. The practices covered include:

- Converting fully slatted floors to partly slatted floors
- Frequent slurry removal (including via pit flushing, scraping, and V-shaped conveyor)
- Solid/liquid separation
- Slurry additives
- Titanium dioxide-based paints
- Outside slurry covers
- Deep bedding substrate type and application frequency
- Dietary manipulations including reduced protein or increased fibre
- Feed additives

This information is supplemented by work done by Wang et al. (2017), who also investigated GHG emissions from manure management in deep-pit, pull-plug, bedding and separation systems. They provide a detailed breakdown and comparison of the GHG and ammonia emissions within each system, and provide analysis on the anticipated changes in methane, nitrous oxide, and ammonia under a number of mitigation practices, including low-protein diets, feed additives, air scrubbing, various slurry covers, and several types of land application.

Van der Heyden et al. (2015) provide a high-quality comprehensive review of air scrubbers and biofilters, covering all aspects of the technology and its impact on ammonia and GHG emissions. Phillipe et al. (2011) review ammonia emissions in pig houses including sources and mitigation techniques, which have substantial overlap with those associated with GHG reduction. Dennehy et al. (2017) conducted a critical analysis of the GHG emission impact of different pig manure management techniques, including storage, solid/liquid separation and anaerobic digestion, while Pomar & Remus (2019) provide an overview of precision feeding in pig production. Finally, much of the information on hydrogen electrolysis was derived from Lourinho & Brito (2020), who provide a comprehensive review of the current state of knowledge on electrolytic treatment of pig wastewater.

Additional practices were considered following discussion with ADAS technical experts in the sector and the AHDB. These practices include:

- Slurry cooling
- Air scrubbing
- Slurry acidification
- Micro-AD
- Hydrogen electrolysis
- Building insulation
- Climate control optimisation
- Total productive maintenance (TPM)
- Precision feeding
- Responsible sourcing

All practices were then grouped according to common themes and a set of key practices were identified to take forward to REA, based on industry trends and feedback from technical experts (Figure 4). The results of the REAs are discussed in section 5.2.1 and full details of each practice can be found in the narrative summary section of the annex (section 10.2). For those practices that were not progressed to REA, brief summaries are provided in section 5.2.3 outlining future potential where relevant.)

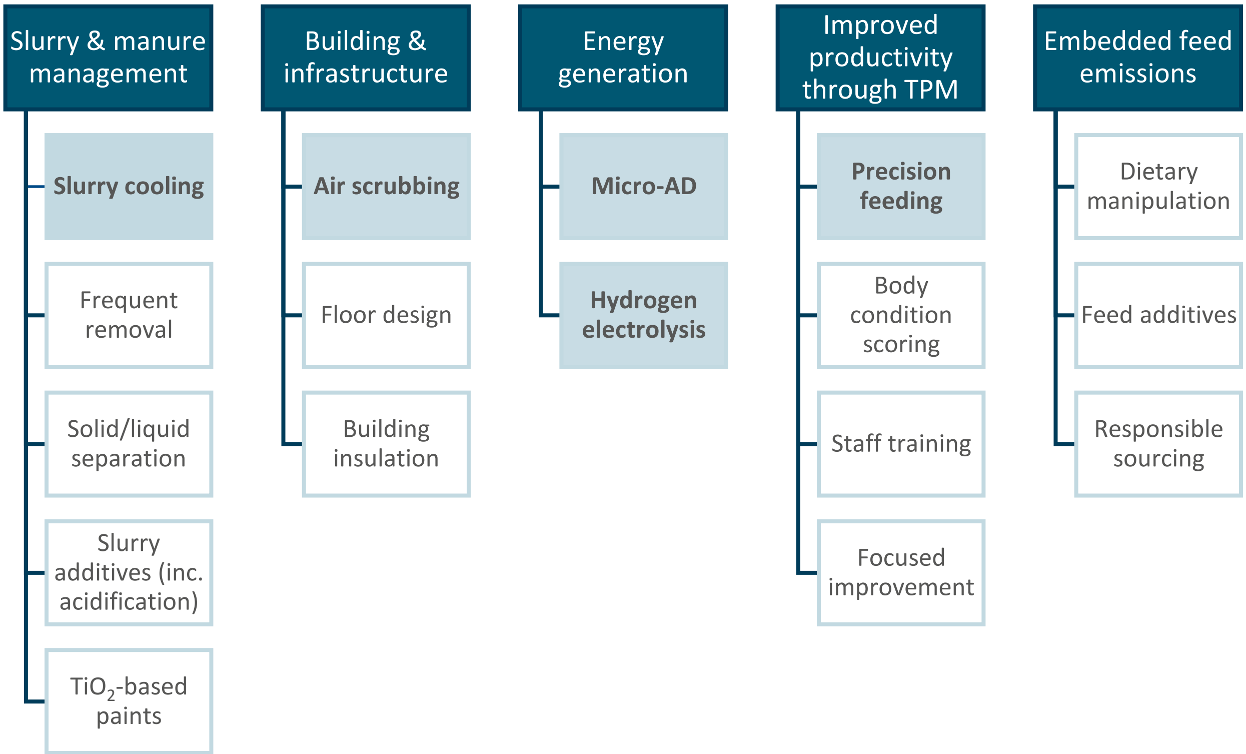

Figure 4. Summary of main practices identified in the initial scoping exercise that may contribute to reducing GHG emissions in pig production. Practices highlighted were chosen to be investigated further via rapid evidence assessment.

5.2. Critical review

The REA process enabled the creation of narrative summaries for several practices that have potential to reduce GHG emissions in the pig sector (Section 10.2). The evidence base for each practice is of varying quality and contextual relevance, and in almost all cases there are knowledge gaps to be explored further. Some of these knowledge gaps may be addressed through a broader and more thorough search process, while others may need additional experimental or contextual evidence. The narrative summaries have also highlighted issues that are common across multiple practices, suggesting a fundamental lack of knowledge or data across the sector. The following sections discuss these knowledge gaps at sector and practice level and suggest next steps to address them. Finally, those practices which were not progressed to REA are briefly summarised, highlighting where there is future potential.

5.2.1. Practices included in REAs

Slurry cooling

Slurry cooling involves pumping cold water through a series of pipes within or under the stored slurry. This draws heat from the slurry, reducing its temperature from 30-35°C to 10-12°C. The reduction in temperature reduces the activity of microbes in the slurry, resulting in a decrease in ammonia and methane production. Ammonia, while not a GHG itself, is associated with indirect emissions of nitrous oxide so reducing ammonia loss may have indirect benefits for N_2O reduction. Reducing ammonia also improves air quality, which can result in lower electricity use for ventilation. By using a heat exchanger, the extracted heat can be used for heating sheds or farrowing areas. A reduction in the use of grid electricity or fossil fuels for heating has additional benefits for reducing GHG emissions.

Slurry cooling is a highly effective method of reducing ammonia emissions from slurry, with Botermans et al. (2010) reporting 30-50% reductions across four European sites. Reducing ammonia indirectly reduces nitrous oxide because ammonia will ultimately contribute to some additional N_2O emissions in the environment (Zhu et al., 2013). Another issue to consider is the implications during slurry application – i.e. the emissions saved during storage may still be released upon application. There is less evidence for impacts of slurry cooling on methane production, but it is likely that slurry cooling also inhibits methanogenic bacteria. This was supported by Hillhorst et al. (2002) who found a 30-50% reduction, although more research is needed to verify these results. Where slurry cooling is used for heating, this will offset fossil fuels or grid electricity, which will have additional benefits in reducing CO_2 emissions, although the savings will depend on the exact implementation. There is a lack of contextual evidence for slurry cooling, so relevant UK case studies are needed to clarify the GHG impact and costs of different types of slurry cooling systems – underfloor, on-floor, and floating – at different installation scales. Slurry cooling is only suitable for slatted systems, which makes it inapplicable to many UK pig farms which are straw-based. Furthermore, slurry cooling is best suited to farrow-to-finish units because the heat can be readily used in the farrowing areas, however this system is also becoming less relevant in the UK context. Slurry cooling is most cost-effective when installed in new buildings under the slurry tank (AHDB, 2019a). It can be retrofitted above existing slurry floors, but there are issues with cleaning under the pipes. The only retrofit option that is recognised as best available technique is the use of floating heat exchangers, but these also have technical challenges around crust formation and freezing, which should be addressed going forward (Santonja et al., 2017).

Air scrubbing

Air scrubbing is an end-of-pipe measure to remove ammonia, dust, and other pollutants from the exhaust air of intensive animal housing. There are 3 main types of scrubber which have different strengths and so are often used in combination as two- or three-stage scrubbing systems.

Both wet acid scrubbers and bioscrubbers are highly effective at removing ammonia, achieving 96% and 70% reductions (Melse, 2009). Biofilters are less effective, achieving 9-50% ammonia reductions (Van der Heyden et al., 2015). Removal of ammonia is likely to have indirect benefits in reducing nitrous oxide emissions because ammonia is associated with increased N_2O formation in the environment. Where bacteria are present (in bioscrubbers and biofilters) nitrification can occur, which increases emissions of nitrous oxide. Van der Heyden et al. (2015) found an average 80% increase in nitrous oxide from bioscrubbers, with one study observing a 200% increase.

Air scrubbers are required on permitted farms, so it would be beneficial for the indoor pig industry to conclusively determine the overall impact on GHG emissions from typical scrubbing systems in the UK context. Another area of future development is in improving the cost-effectiveness of air scrubbing, which typically has high installation and operating costs – £26-30 investment and £7-9 annually per pig place for a wet acid system in the Netherlands (Sontanja et al., 2017). One method to offset some of this cost might be through increased valorisation of the ammonium sulphate produced in wet acid scrubbers. This is a by-product of air scrubbing where ammonia reacts with sulphuric acid to produce ammonium sulphate, which is a fertiliser containing 6-7% nitrogen. This can reportedly earn an income of £0.30 per kg of nitrogen recovered in a 0.1 ammonium sulphate solution, with potential other industry applications (Santonja et al., 2017). Use of this fertiliser in crop production systems can offset some artificial nitrogen fertilisers manufacture emissions. Finally, some types of biofilter have been shown to reduce methane emissions by 43%, although only under long residence times (Van der Heyden et al., 2015). Further work is needed to determine the practicality of these long residence times, and their relationship with increased nitrous oxide emissions.

From the evidence collated in this view it is important that a farmer understands the wider consequences of installing air scrubbing technologies in their housing as there is the risk that although ammonia emissions are reduced, the increase in direct N_2O emissions may outweigh the reduction in indirect N_2O emissions.

Micro-Anaerobic Digestion

Anaerobic digestion is the breakdown of organic matter by microbes under anaerobic conditions to produce biogas – a mixture of methane, CO_2, and other gases. With minimal purification, biogas can replace natural gas in boilers or CHP units to produce heat and electricity. After digestion, the remaining material (digestate) is an effective fertiliser and can be spread on land in the same way as manure or slurry. AD in Europe has been dominated by large, centralised biogas production sites, but there is increasing demand for micro-AD, which can produce enough electricity and heat for a medium-sized farm using slurry, manure or crop waste.

Micro-AD is a promising method of reducing GHG emissions on pig farms because it can convert waste products (manure or slurry) into energy, without impacting the fertiliser value (Makádi et al. 2012). The main impact of micro-AD is the ability to offset grid electricity and fossil fuel use through the combustion of biogas. GHG emissions from biogas are 0.00021 kg CO_2e/kWh, which is much less than UK grid electricity (0.23314 kg CO_2e/kWh) (UK Gov, 2020). In this respect, the best implementation of micro-AD is on farms with large energy requirements, such as those with farrowing units. The overall GHG emission impact of micro-AD will depend on the size of the site, the number of animals, the size and type of AD installed, the site's electricity and heat requirements, and several other factors. However, due to a lack of relevant UK case studies, it is difficult to quantify the exact emission savings. There is also evidence that anaerobic digestion of slurry reduced overall GHG emissions during storage and application versus undigested slurry (Sajeev et al., 2018). However, there are also mixed findings in storage and application individually, so more work should be done to confirm these findings. An additional point to consider is the use of additional feedstocks, such as silage, straw or beet, which can increase gas yields although they have additional embedded emissions associated with their production. More work is needed to comprehensively evaluate the relative life cycle GHG emissions of different feedstocks. The dairy sector is also a potential candidate for micro-AD so it would be wise to share knowledge between the two sectors where possible.

Hydrogen electrolysis

Hydrogen electrolysis is a method of producing hydrogen gas (H_2) from liquid organic waste (i.e. slurry wastewater). The process works using a microbial electrolysis cell (MEC) which contains electrogenic bacteria. The bacteria break down organic molecules and, with application of external electricity, produce hydrogen gas, methane and CO_2. Hydrogen is a clean-burning, high-energy fuel source that may have potential future applications. Hydrogen electrolysis is not yet viable on a commercial scale but may have initial applications as a post-treatment of anaerobic digestion. Further research is needed to optimise the production of hydrogen and to scale the technology.

Hydrogen electrolysis of pig wastewater is a highly promising technology for reducing GHG emissions in pig production. It can potentially remove pollutants while generating hydrogen and biogas, however, as this technology is relatively new, there are no case studies of it being applied at farm-scale. Commercially viable hydrogen production from pig wastewater on-farm would be a promising next step in the development of the technology, but it is likely that there are issues to be addressed at the laboratory scale first. These include optimisation of the reaction parameters, including temperature, pH, reactant used, type of electrogenic bacteria and the materials used for the anode and cathode (Kadier et., 2014). Even assuming the process can be optimised, and can work economically at scale, there is still a question of whether there is a market for the hydrogen gas and at what price-point.

Hydrogen is well-placed to be a future fuel, particularly for applications that require more torque than can be obtained from electric batteries, such as industrial machinery and heavy vehicles such as tractors. The current method of producing hydrogen, water electrolysis, is energy intensive and expensive, so hydrogen electrolysis of pig wastewater presents a potentially cost-effective alternative (Zhang & Angelidaki, 2014). A likely initial implementation for hydrogen electrolysis could be as a post-treatment stage of anaerobic digestion, providing additional purification of digestate wastewater. There are also potential applications of using microbial electrolysis cells to enhance the stability and yield of AD biogas production, although as with hydrogen electrolysis there is still a large evidence gap (Lourinho & Brito, 2021).

Precision feeding

Precision livestock feeding aims to precisely match animal nutrient supply to nutritional requirements, based on collected data such as age, weight and performance. In practice, this ranges from manually supplementing feeding to sows based on litter size, to automatic feeding systems that monitor the feed intake and average weight of a group of finishing pigs, precisely adjusting the feed ration on a daily basis to minimise excess nutrition. Precision feeding allows each animal to achieve optimal production for the minimum amount of feed, which has impacts on production costs and, given that feed accounts for 70% of the GHG emissions in pork production, GHG emissions as well.

Precision feeding on an individual level is already widely practiced in the UK farrowing sector, with sows given diets that are adjusted based on parity, body condition and reproductive performance.

This can be done manually or using automatic feeders and is also common in the dairy sector. The main opportunity for precision feeding in the UK pig industry is likely to be the implementation of precision group feeding on growing/finishing units. This consists of two feed blends – one high energy and one low energy – that are blended in slightly different proportions each day to track the changing dietary needs of the pigs as they grow (Pomar & Remus, 2009). This would typically be distributed using automated feeders that take into account the age of the group, the average feed intake (calculated by the feeder) and the average weight (calculated by scales positioned in front of the feeder). These systems can be implemented in any finishing system, either straw or slat based, which gives them broad application across the UK sector. It is likely that many new build units are already applying this, so sharing that knowledge via case studies would support the rest of the industry in following suit. There can be substantial investment costs in these types of systems, however 8% cost savings due to reduced feed have been consistently achieved with no impact on productivity (Pomar & Remus, 2009). The exact GHG impact is harder to quantify but reducing feed while maintaining productivity will reduce GHG emissions from of pig production. Andretta et al. (2018) provide the only study that specifically investigated the impact of precision feeding on GHG emissions, reporting a 6% reduction in life cycle GHG emissions after implementation of individual precision feeding. Precision feeding is a form of precision livestock farming, which aims to improve the efficiency of livestock production through monitoring, modelling, and managing aspects of animal production (Tullo et al., 2019). With advances in sensing technology, including cameras that utilise artificial intelligence, it is plausible that precision farming technologies will be able to further improve animal productivity and welfare going forward.

5.2.2. Sector-wide evidence gaps

Focus on ammonia rather than GHG

One of the main issues in the scientific literature around GHG emissions in the pig industry is that much of the research has previously focused on reducing ammonia emissions. This is to be expected, given the air quality legislation and the implementation of the best available technique (BAT) guidance (Sontanja et al., 2017). With a recent focus on Net Zero, it has become apparent that there is an evidence gap regarding GHG emissions in the pig sector. Going forward, applied research must include measurements of GHG emissions alongside ammonia, as some authors have already done. Ammonia has no direct impact as a GHG, although some of the nitrogen that is ultimately deposited will be nitrified by soil bacteria to indirectly produce nitrous oxide (Zhu et al., 2013).

Lack of case studies/contextual evidence

Many of the narrative summaries were restricted in the availability of detailed, UK farm-level data. The effectiveness (and economic viability) of most practices will vary depending on the individual farm. The use of reviews is an effective way of determining the average impact of a practice across a range of different farms, but for implementation on a practical level, farmers need more contextual information than is available in the evidence base. Much of the information on costs and best practice is taken from case studies in Denmark and the Netherlands. A suggestion for AHDB is to maintain a catalogue of case studies, collecting relevant information about each farm (size, location, production system, herd numbers, etc.) and the details of the practice that is being implemented. This way, farmers in a similar situation will be able to get a much more accurate idea of the costs, challenges, and benefits associated with implementing a practice. In communicating evidence to farmers, it will be important to make it clear what size and type of operations will be suitable for a given practice – e.g. small, medium or large enterprises, permitted or non-permitted farms, those on slats or on deep-bedding, those with farrowing units or only finishing, and those with the option to build new or only retrofit.

Lack of evidence for life-cycle manure effects

Many of the GHG mitigation practices in pig production involve manure management, be it separation, more frequent removal, cooling or anaerobic digestion. As slurry/manure/digestate is typically applied to land at some point, it is important to consider the emissions during application as well as during storage. There may be no overall benefit to reducing GHG emissions during slurry storage if those emissions are then released upon application, so where ammonia or nitrous oxide emissions are prevented during storage, mitigation measures must be put in place during application to reduce emissions. This can be done by rapid incorporation into the soil, and by utilising low emission spreading techniques, which are discussed in detail in the AHDB Dairy rapid evidence assessment (Gill et al., 2020).

Lack of literature on total productive maintenance (TPM)

Over the last 18 years, the UK indoor pig industry has reduced its global warming potential by 37% (Ottosen et al., 2021). This has largely been driven by improved genetic performance and management, resulting in increased growth rate, better feed conversion ratio, more piglets/sow/year and reduced piglet mortality. Given the dramatic improvements over the last two decades, there is now a smaller window of opportunity to improve these traits. One method to address this is the implementation of total productive maintenance (TPM), which applies process controls throughout each stage of production in order to increase consistency and achieve marginal improvements which multiply across the system. There are nine pillars of TPM:

- Autonomous Maintenance
    - Building maintenance into normal routines, such as post-lactation body condition scoring or weighing sows between parities
- Focused Improvement
    - Identifying underperforming outliers and adjusting accordingly, such as giving additional feed to sows with smaller than average litters

- Planned Maintenance
    - Creating measures that address problems before they occur, such as vaccination programs and biosecurity measures
- Quality management
    - Creating clear quality specifications at each stage of production, such as criteria for replacement gilts or sows entering subsequent parities
- Early/equipment management
    - Managing the early stages of the production cycle, such as appropriate service ages and weights for replacements
- Education and Training
    - Ensuring staff are properly trained, especially around technical jobs like artificial insemination
- Administrative & office TPM
    - Ensuring recorded data is accurate so that it can be used to support management decisions
- Safety, Health & Environmental conditions
    - Ensuring the production process conforms to health and safety standards and relevant environmental regulations
- Routine maintenance
    - Ensuring maintenance is carried out regularly, such as on buildings, equipment and animals (e.g. vaccinations, health interventions)

Given the challenges of continued improvement in GHG emissions from the pork sector, TPM is an essential tool in continuing progress. However, many of the themes overlap with other ideas such as precision feeding, precision livestock farming and other lean management concepts. There would be significant benefits in creating a short report that introduces the concept of TPM to pig farmers, with clear definitions of the terms and relevant case studies to demonstrate what each means in practice.

5.2.3. Additional practices and future developments

There were a number of other practices that were screened at the initial stages of this REA process, but insufficient evidence was found to take through the entire REA process, or it was agreed that they were outside of scope. These practices are summarised below, with a brief description of the practice and discussion on future applications where appropriate.

Solid/liquid separation

Involves separating the solid and liquid fractions of slurry to prevent interactions that lead to production of GHG emissions. Slurry can be separated via several methods, including presses and centrifuges although generally energy use is a restriction. The Welsh Slyri Project is working to develop dewatering and purification systems to manage slurry on farm.

Frequent slurry removal

Includes a range of systems to remove slurry or manure more frequently from housing to limit the production of GHG. In pits it can be done via automatic scraping, flushing or conveyor belt systems. There is a lack of consistent evidence regarding impact on GHG emissions.

Dietary manipulation

There is varying evidence for the role of dietary manipulation in reducing GHG emissions in pigs. Some studies have suggested that reducing the crude protein content reduces ammonia emissions and phosphate use, although there are operational challenges around splitting sexes which are impractical for most farms. Other techniques include a range of feed additives, including enzymes, yucca extract and probiotics, although only bacillus is approved as best available technique.

Reduced embedded emissions from feed

Increasing the proportion of homegrown feeds, particularly proteins, can reduce the GHG impact of feeding in pig operations, see AHDB arable rapid evidence assessment (Stockdale & Eory, 2020). Also requesting certified deforestation-free soya meal.

Slurry acidification and other additives

Acidification shows promise in the dairy sector, but challenges around handling sulphuric acid and the volumes required to have an effect. Other additives lack evidence base; these include tannins, essential oils and enzymes.

Energy efficiency

Building insulation is an underdiscussed topic in GHG reduction, but it will likely have an impact where heating is used, e.g. in farrowing units. Farm-wide techniques such as annual energy audits can highlight areas of energy inefficiency, while switching to LED lighting is a cost-effective way to reduce energy use.

Precision livestock farming

The development of sensors, artificial intelligence and big data could have future applications in monitoring herd health and improving welfare and productivity. It is important that GHG emissions are specifically considered in evaluations of these new technologies.

Slurry pit titanium dioxide paint

Some early research suggests that titanium dioxide paint on the walls of slurry pits can impact the bacterial populations to reduce GHG emissions, although more work needs to be done to confirm these findings on a practical level.

Bedded systems

Likely to become more prominent in the future due to the drive towards higher welfare standards, so it is important to determine how to minimise emissions from deep bedding. GHG emissions are affected by temp, pH, depth, humidity, C/N ratio, density etc. There is a need to determine the impact of bedding material and amount and frequency of application. Other potential systems such as the Xaletto system may have future potential.

Outside slurry/manure management

There are a broad range of different covers for slurry and manure stores, both natural and synthetic, and all with varying evidence of effectiveness. Other potential techniques for manure management include aeration, biofiltration, composting and vermifiltration, although all lack evidence. One key issue is to maintain energetic and agronomic value.

Slurry spreading

See AHDB dairy rapid evidence assessment (Gill, et al, 2020). In general, GHG emissions from slurry spreading can be mitigated by avoiding waterlogged soils, matching application to crop requirements and using low emission spreading equipment such as trailing shoe/hose or injection.

6. Potatoes

6.1. Scoping exercise

The initial scoping exercise aimed to find broad reviews of Net Zero practices in the potato sector. Although no reviews were found that focussed on Net Zero practices, Groves et al. (2011) provides a review of the sustainability of potato production in the UK including a consideration of GHG emissions. The biggest opportunity for addressing the GHG emissions from potato production is around the optimisation of nitrogen fertilisers, due to the GHG emissions associated with their production and the N_2O emissions after application. The other key contributor to GHG emissions from potato production is energy consumption. There are a number of elements in the production system that are consumers of energy including the cultivation, planting and harvest of potatoes, irrigation use and also storage. Cultivations in potato production tend to be intensive, so opportunities for reducing the intensity of cultivations would reduce GHG emissions. Potato production is a major user of irrigation water; there are CO_2 emissions required to provide the energy for pumping water and potentially increased N_2O emissions from the anaerobic conditions of saturated soils. Optimising potato irrigation could reduce emissions.

Based on the suggestions within Groves et al. (2011) and discussions with technical experts, target practices for GHG emission reduction were identified for taking forward to the next stage of the REA. The list of practices was limited as many relevant practices had already been considered as part of the REAs produced for EFI in the report on cereals and oilseeds sector (Stockdale & Eory, 2020). For example, although N use efficiency is an important target for reducing GHG emissions from potato production, this had been addressed in the previous report with narrative summaries produced for specific practices, such as ‘Optimising N addition and avoiding N excess’.

Practices to do with optimising irrigation use were also excluded from the current study. It was felt that there would be insufficient evidence on this topic with regards to Net Zero. However, this may be an area that needs greater focus, particularly with the potential that summers are predicted to become drier under climate change scenarios (Met Office, 2019).

In contrast, even though the cereals and oilseeds sector Net Zero REAs had considered reducing cultivation intensity as one of its practices, it was felt that potatoes, and root crops in general, are sufficiently different to consider whether there was relevant data that could provide potato-specific guidance. Groves et al. (2011) had found that there was only limited data available on the impacts of different cultivation systems in potato production, so it felt pertinent to explore the literature landscape since then.

In the scoping exercise, it became clear that improving energy efficiency of potato stores had significant potential for reducing the GHG emissions of potato production. Potato storage is a complex process with many risks of inefficiencies occurring (Cunnington, 2019). Swain (2010) found a three-fold difference in energy use between the highest and lowest users in a survey of 36 potato stores. It has been suggested that many older potato stores do not meet modern standards for insulation (Carbon Trust, 2010). Addressing these inefficiencies has the potential to reduce GHG emissions. However, it should be noted that much of the evidence cited on potato store efficiency is potentially outdated and the current energy performance of stores may be higher due to upgrades of stores or replacement with new stores built to higher energy efficiency standards.

There are a number of interventions for improving the energy efficiency of potato storage; for example, the British Potato Council (now AHDB Potatoes) published a guide on the '12 steps to energy efficient storage' (Clayton et al., 2007). Several of these practices were identified as being appropriate for the REA process (i.e. where research syntheses may be available).

From the initial practice scoping exercise and using input from technical experts in the sector, the following practices were identified as potentially having significant GHG reduction and a sufficient evidence base to be progressed to the next stage of the REA (Figure 5).

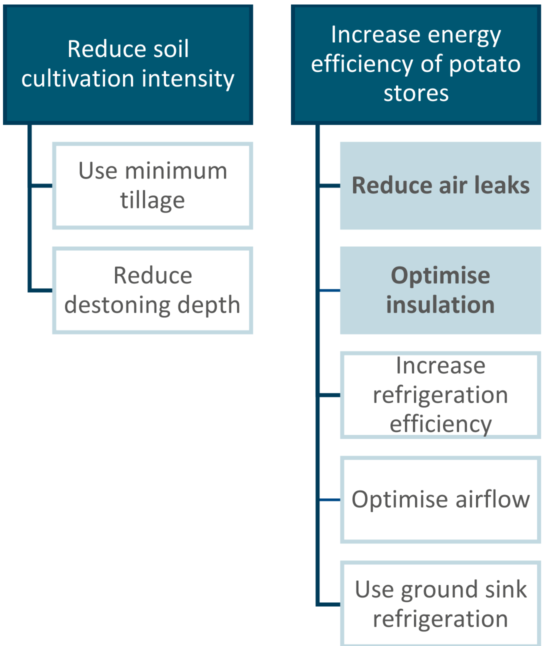

Figure 5. Summary of main practices identified in the initial scoping exercise that may contribute to reducing GHG emissions in potato production (excluding those already captured in previous REAs for the EFI). These practices were taken through to the rapid evidence assessment though sufficient evidence was only found for the two practices highlighted by a blue background.

6.2. Literature search

6.2.1. Reducing cultivation intensity

There were also no relevant research syntheses on reducing cultivation intensity in potatoes. Although reducing cultivation intensity has been championed (e.g. in the farming press; Robinson, 2013), there is little published data on the use of non-plough-based cultivation systems in potato production. In order to provide guidance on potato storage and cultivations, the search was broadened to include grey literature. The key literature found during this search were two reports produced for the Potato Council (now AHDB Potatoes) on cultivation depth (Stalham & Allison, 2016) and cultivations and cover crops (Silgram et al., 2015). The AHDB guide to arable soil management (2020) provides guidance on potato cultivations, including the factors to take into account when making decisions on whether to reduce cultivation intensity. However, this evidence base was deemed insufficient as the basis for creating a narrative summary, particularly because they provide only limited insight into GHG emission reduction.

6.2.2. Improving potato store efficiency

During the development of search parameters and optimisation of search terms, it became apparent that there was very little research literature on Net Zero practices related to potato storage. A focus on energy efficiency also failed to provide research syntheses on potato storage. This lack of detail in the scientific literature on potato stores is due to two reasons. 1) Given the variability and scale of potato stores, conducting robust experimental work is challenging; 2) storage improvements have been driven by industry with many initiatives focused on energy efficiency led by major potato packers, retailers, and food processors (Groves et al., 2011) and therefore published papers and reviews have not been completed in the same way as for some of the other practices.

Outside of syntheses, a small body of literature on efficient potato storage was identified. A significant amount of research is conducted by Sutton Bridge Crop Storage Research (CSR), which is owned by AHDB. With extensive controlled environment storage facilities, Sutton Bridge CSR can provide trials on all aspects of storage. A priority of research into potato storage has been on maintaining the quality and quantity of potatoes stored. Given that potatoes may be stored for 10 months (Carbon Trust, n.d.), making sure that conditions are maintained to reduce the risks of disease, pests, sprouting, moisture loss and damage are vitally important. Alongside research into maintaining the quality and quantity of stored crop, they also offer support on improving the efficiency of potato stores. Guidance is provided to the industry through publications (e.g. The Potato Store Manager's Guide; Cunnington et al., 2019), their storage advice line, the AHDB Storage Network and other KE activities. Work funded AHDB and the Potato Council (now AHDB Potatoes) has explored potato store efficiency. This includes consideration of variable-speed fans

(Cunnington et al., 2010) and comparison of stores (Swain, 2010, and Swain et al., 2013). This report has also drawn on case studies, such as from the Carbon Trust (2010) and AHDB (2019c). One difficulty faced in searching for data was the inclusion of unpublished data in articles; for example, Scrivener (2015), in an article in the farming press, makes reference to data from a series of carbon audits conducted by Sutton Bridge CSR. Further reference to this data was not found online.

6.3. Critical review

6.3.1. Practices included in REAs

Unlike with the pork and protected horticulture sectors, there were no research syntheses available for the targeted practices in the potato sector. The grey literature did provide what was judged to be robust recommendations on practices that could support a reduction in energy use. However, within this grey literature there was a lack of insight into the costs and GHG emission reduction benefits of the different practices. For that reason, only two practices – sealing air leaks in potato stores and optimising insulation in potato stores – were deemed as suitable for developing into narrative summaries for use in EFI. The reasoning for the inclusion of these two practices was that these are often responsible for poor energy efficiency in potato stores and there are indicative costs available and quantification of the extent of energy use reductions resulting from these practices. Narrative summaries for these are presented in **Appendix 10.3**.

Sealing air leaks: Structural air leaks can lead to ingress of warm air leading to increased energy use for refrigeration and/or ventilation to maintain correct environmental temperature for the stored crop. By reducing structural air leaks, energy requirements can be reduced, reducing costs as well as the associated GHG emissions from the production of that energy.

Optimising insulation: Poor insulation in potato stores will increase energy use for refrigeration and/or ventilation used to maintain correct temperatures for stored product. By upgrading or repairing insulation, energy requirements can be reduced, reducing costs as well as the associated GHG emissions from the production of that energy.

Although these have been presented as two separate practices for the purpose of the narrative summaries, there is overlap between them. Structural air leaks in potato stores may be caused by poorly fitting or damaged insulation. In addressing poor insulation through the repair of existing insulation panelling or through the addition of further insulation, air leaks may be sealed.

For both identified practices, the main evidence used is from the Potato Store Manager's Guide (Cunnington, 2019). This is based on significant expertise in the field of potato storage and confidence can be placed in the information provided. It draws on a range of literature, including research produced on behalf of AHDB Potatoes (previously Potato Council). This research was also consulted, particularly to provide data for the impact of practices. Internet searches identified only a few data sources including data on costs and GHG emission reduction. For information on costs and potential GHG emission reduction, case studies were used. The relevance of this data is discussed in the following section.

6.3.2. Sector-wide evidence gaps

Reducing cultivation intensity

Reducing intensity of cultivations was addressed in a previous REA (Stockdale & Eory, 2020), however, it was felt that this could not be considered from a root-crop perspective. Non-plough-based cultivation systems are being used in potatoes, although significant movement of soil is still required. A reduction in cultivation intensity (e.g. shallower tillage, fewer passes) will generally require less fuel and, therefore, produce lower GHG emissions. There is also a suggestion that lower intensity cultivations lead to increased soil carbon, though as discussed in Stockdale & Eory (2020), there is no conclusive evidence when assessment of a deeper soil profile is considered across a wide range of studies. For growers, the important question is to what extent can cultivation intensity be reduced without impacting on yields.

Two aspects were considered for potatoes: can we use non-inversion cultivation practices instead of ploughing, and can we reduce the depth of cultivation (i.e. destoning depth for creation of a potato bed). Given that root vegetables have different requirements from cereals and oilseeds, it was expected that evidence of the impact of these would have been collected specifically for root vegetables. However, in the search of the literature, only limited experimental evidence was found. The data presented in Stalham & Allison (2016) suggest that there are opportunities for decreasing GHG emissions (through lower fuel use) by lowering cultivation intensity. Silgram et al. (2015) found that yields did not differ between plough and non-inversion tillage practices, though they did not collect data on fuel use, which means assumptions about GHG emissions for the different practices cannot be made. However, there were no other identified sources that provided relevant information in a UK-context.

There is likely to be a significant body of knowledge within the farming community on the use of these cultivation practices that is not based on formal experimental studies. The AHDB guide to arable soil management (Newbold et al., 2020) provides clear guidance on the cultivation options that are available for potato growers, but this does not cite specific evidence sources for this guidance. Instead it is the result of the combined experience of multiple experts. Anecdotal evidence (e.g. de la Pasture, 2016) would suggest that some farmers see shallower cultivations as presenting greater risk. An important question is whether building the evidence base through further formal experimental work will help to convince farmers to adopt shallower cultivations, or if it will be more effective to use case studies and demonstration farms.

Potato storage

All practices identified in the ‘12 steps to energy efficient storage’ (Clayton et al., 2007) have the potential to reduce energy use and, therefore, GHG emissions. Clear practices have been identified that improve the efficiency of storage. For example, the Potato Store Managers’ Guide produced by Sutton Bridge provides guidance that not only enables efficiency to be maximised, but also productivity through managing potato stores to minimise loss of quality and quantity. Although not directly addressing GHG emissions, reducing energy use means reduced emissions from grid electricity generation. What is lacking from the evidence base is guidance on what each practice would cost to implement and the extent of its potential for decreasing costs and GHG emissions. This information is important when making decisions on the changes to make to the potato store.

The challenge with generating data for individual practices is that their costs and effectiveness are dependent on the existing conditions of the potato store. Equipment and structure age, size, storage type (boxes vs bulk stores) and location (e.g. the microclimate) will all have an influence. For example, a modern, purpose-built store will likely not need further intervention to reduce energy requirements. The use of the store will also influence the potential for energy savings, with storage temperature, length of storage duration, time of the year potatoes are being stored, and configuration of the store all determining energy requirements. For example, stores for pre-pack potatoes (potatoes sold to consumers as whole, raw potatoes) are stored at 2-3°C whereas processing potatoes (i.e. those sold for processing into crisps, chips, etc.) are stored at 7.5-10°C; much greater energy will be required for storing pre-pack potatoes and so the potential for reducing energy consumption, and therefore GHG emissions, is greater.

The collection of the data itself also presents challenges. Being able to make interventions in a reproducible approach given the scale of potato stores makes the process prohibitively expensive. There are also many confounding variables: for example, potato store efficiency will depend on weather conditions, with temperature having a significant impact on energy needs (Swain et al, 2013). Measuring energy use before and after changes to a potato store may be significantly influenced by the weather conditions in the periods before and after the changes.

Case studies of existing stores with assessment of energy efficiency provide insight into the influencing factors. Swain et al. (2013) present case studies for four potato stores. The energy use of the stores was monitored with three stores having data collected before and after improvements were made. The case studies demonstrate the benefit of this data collection method (e.g. one case study showed that the replacement of a fan increased energy efficiency by 10%), but also the disadvantages (e.g. the changes were very specific, which meant that they would be applicable to only a small number of potato stores).

To get a broader picture, other approaches have been attempted for correlating the use of practices with energy performance. Swain (2010) compared the energy performance of 36 stores against the characteristics of each store. The study found weak correlations for reduced energy efficiency for stores over 10 years old, stores where insulation thickness was below 75 mm, stores where sliding doors were used instead of roller shutters and where inverter drives were not being used. There was no clear correlation between energy use and target store temperature. This lack of clear relationships could be due to confounding factors associated with the variability between stores. (e.g. a store might have thick insulation but may also have poor sealing).

Another approach is to model energy efficiency through computer simulation of potato stores. Using a model of a potato store, Swain (2010) simulated changes in potato store characteristics and quantified the impact on energy use. Increasing target temperature, using thicker insulation and reducing air leaks all led to decreases in energy use. Swain et al. (2013) continued these simulations. In a comparison of best- and worst-case scenarios for air leakage, they found that there was a potential for up to 33% and 50% savings in energy use by reducing air leaks for pre-pack and processing potatoes, respectively.

With so many options for improving efficiency, potato store managers will need to determine which to invest in. As the potato store becomes more energy efficient, the efficiency gains from each new change will lessen. For example, Swain et al. (2013) highlight the diminishing returns from increasing insulation thickness with the marginal gain from increasing insulation thickness on an already well-insulated store being quite limited. Swain (2010) used modelling to demonstrate how the energy efficiency impact of combining three improvements (increasing target temperature, increasing insulation thickness and reducing air leaks) was less than the aggregation of the energy efficiencies for each improvement made independently.

Given the bespoke nature of potato stores and the multitude of options for improving store efficiency, expert advice should be sought. AHDB’s StoreCheck (provided through Sutton Bridge CSR) provides a potato store audit that helps identify opportunities available to potato store managers for improving their store’s energy efficiency. The audit will be able to draw on much larger data resources than are publicly available, as well as offer expertise to provide advice specific to each individual store. To encourage potato store managers to seek out opportunities for improving energy efficiency, it will be important to be able to demonstrate the potential value to them. Where changes are being made, it is essential to capture these in case studies to provide an evidence base for store managers looking to make upgrades.

One thing to note is that, for the data sources drawn on here, data was presented in terms of reducing energy/electricity use rather than in terms of reducing GHG emissions. The purpose of this REA for EFI is to identify Net Zero practices. It can be assumed that a reduction in electricity usage would lead to a proportional reduction in GHG emissions associated with the production of that electricity where stores are run on grid electricity. However, with regards to work conducted in this area, the focus has been on reducing energy consumption, and therefore reducing costs. This is understandable given that electricity costs are a substantial component of the overall cost for producing potatoes. Therefore, GHG savings are usually a co-benefit of the overall aim of reducing costs from potato storage. The actual GHG savings will depend on not only the reduction in electricity use but also the mix of electricity being used. If renewable energy is being used, then adoption of these practices may not have an impact on overall GHG emissions. Though, if that saved renewable electricity is used to displace non-renewable electricity then GHG benefits will be seen.

6.3.3. Additional practices and future developments

Reducing cultivation intensity

Preparing soil for growing potatoes involves cultivation (usually ploughing followed by secondary tillage) to break up the soil and form ridges, followed by removal of stones and clods from the ridges. This process needs to take place when the soil is sufficiently dry to avoid damage to the soil (Newbold et al., 2020). Deeper cultivations require more fuel due to more soil needing to be moved, so reducing cultivation depth would be expected to reduce fuel use and therefore GHG emissions.

Stalham & Allison (2016) conducted field experiments to identify optimum depths for destoning and requirements for secondary tillage. They found destoning at depths below the commonly used depth did not reduce yield (even increasing yield in some cases). Shallower destoning led to reduced fuel use, faster work rate and less wear on machinery. The fuel use savings were on average 16 l/ha, which would potentially be a GHG saving of approximately 43 CO_2 kg/ha (assuming 2.67 CO_2 kg/ha per litre of diesel). An additional benefit is that shallower destoning depth also means that primary cultivation depth can be made shallower. Plough vs non-inversion cultivations were compared, but these trials did not include replication, preventing a robust comparison between the practices.

The results also showed that the optimum depth varied with conditions. Soil type, soil condition and the stoniness of the soil were found to influence optimum destoning depth. Operators would need to show adaptability in order to match the correct depth with the conditions. This would necessitate knowledge of the variability in conditions across the field and require an understanding of and ability to adjust to those conditions. There would be learning costs associated with enabling operators to do this, and potentially new equipment may be needed to allow the fine control of settings needed across variable soil conditions. However, given the lower labour costs (due to faster work rates) and fuel costs, the additional learning and equipment costs may be outweighed by the savings.

Silgram et al. (2015) conducted similar field experiments and found no significant difference in yield with shallower destoning. They also found no significant difference in yield between plough and non-inversion cultivations. Although fuel use was measured, due to the small size of the experimental plots, this data was not assessed. This means that costs and potential GHG savings are unclear.

Given that the data presented in Silgram et al. (2015) and Stalham & Allison (2016) was collected across more than 50 replicated block experiments taking place over multiple years and sites, it suggests that it is robust. It also demonstrates that it could be a cost-effective practice. As described in section 6.2.1, there are likely to be barriers to its uptake (e.g. perception of greater risk associated with shallower destoning). The potential for using lower-intensity cultivation also needs to be placed in the context of the rotation; where rotational ploughing is used to address weed problems, the most appropriate time in the rotation for ploughing is likely to be before potatoes. Newbold et al. (2020) suggest taking a strategic approach to potato cultivations, with the choice of practice down to the specific conditions at the time. Although additional field experiments may provide some additional value in encouragement of uptake, possibly through demonstrating its applicability to a wider range of soil types and locations, it may be more valuable to give farmers the confidence to use lower-intensity practices and the knowledge to adapt to the conditions. This could be through knowledge exchange activities, such as demonstration of it in practice (e.g. through the AHDB Strategic Potato Farms).

Potato storage

Aside from sealing air leaks and optimising insulation, there are other practices that can be used to improve potato store efficiency and, therefore, reduce GHG emissions. Given the age of available data sources available, some of the information on these may be outdated. These were not taken forward to a narrative summary, due to there being less data available, but should be considered by potato store managers when investigating improvements to potato store efficiency. Key practices are highlighted in this section.

Good maintenance and monitoring

The Carbon Trust (2006) suggested that an important opportunity for improving the energy performance of general cold stores and stand-alone refrigeration units is in having good maintenance. Improvements in energy efficiency may result from keeping equipment in a clean condition, testing equipment regularly and having an annual service of equipment and the store. Not only will servicing reduce the likelihood of equipment failure, but it can help equipment stay at optimum efficiency. Alongside professional servicing of equipment, more frequent checks by the potato store manager should take place. For example, there should be an annual service of refrigeration equipment by a professional, alongside more frequent checks made by the potato store manager covering, for example, the calibration of temperature and humidity sensors (Cunnington, 2019). However, being able to provide an estimate of the impact that would have on energy use, costs and GHG emissions would not be possible due to the variability in store design and system types.

Fitting an electricity meter can provide information that store managers can use to track energy usage. This can allow benchmarking of energy performance against the best performing potato stores (for example, by comparing kWh use per tonne of stored potato). This can give an indication of the potential value in upgrading the potato store. Regular recording of electricity consumption with a comparison against significant events (e.g. when large volumes of stored potatoes are removed, particularly warm or windy days, etc.) or when equipment is being used in isolation can reveal where energy efficiency may need improving. FEC Services (2008) present a case study where the installation of an electricity meter provided evidence that led to a major refurbishment of a potato store. Sub-meters on individual equipment can provide further detail on where energy efficiency could be improved. For example, while monitoring performance of refrigeration systems in potato stores, Swain et al. (2013) found a wide range performance coefficients (the ratio of cooling capability to energy input), showing that there is considerable opportunity to gain energy efficiency improvements through upgrading equipment. There are costs involved with the installation of electricity meters and also learning costs associated with using the collected data effectively, particularly when large amounts of data are generated.

Aligned with the use of electricity meter is the accurate monitoring of store conditions and the use of responsive control of store equipment. Monitoring conditions allows equipment to be run at the optimum level when, for example, paired with variable speed drives. This can be integrated with forecasting systems that can be used to adjust cooling to suit expected weather conditions; for example, by delaying refrigeration cooling if there it is forecast to be cool ambient air available for cooling (Cunnington, 2019).

Variable speed drives on fans and pumps

The extent of refrigeration and airflow cooling needs in a potato store will depend on the external weather conditions. Being able to quickly and accurately adjust refrigeration and ventilation settings to fit the required level of cooling allows energy use to be optimised. Part of this is being able to measure conditions inside, and potentially outside, the store so that the level at which the equipment is running can be adjusted.

Variable speed drives enable equipment to operate at the most efficient speeds for conditions and, therefore, avoid excess energy use (Cunnington et al., 2010). With drives running at a lower speed, energy use is greatly reduced. For example, a fan running at 80% of its full speed uses about half the energy of one running at 100% (Cunnington, 2019). Swain et al. (2013) found that upgrading the condenser fan could increase whole system efficiency by 10%. Given that the energy consumption of a fan for a single season can be equivalent to the capital cost of a new one, upgrading should be based on the potential savings. UK-specific return on investment figures were not found, but a study in Wisconsin found that the use of variable-speed fans could reduce energy for long-term storage by up to 65% , with a one-year return on investment (Sanford, 2006).

An important consideration is the configuration of the system. If fitting variable-speed fans into a system designed for higher airflow, there is a risk that when the fans are running at lower speeds, air distribution within the potato store may be affected (Cunnington, 2019). Potato stores should be configured to provide optimum conditions throughout the store; changes to air distribution that lead to inconsistent conditions throughout the store may have a detrimental impact on potato quality. This would suggest that changes to potato stores should take a holistic approach where each aspect is not considered in isolation. Expert guidance would be required for this.

Other practices and upgrades for potato stores

There are a range of modifications that can be made to potato stores, ranging from relatively minor changes, such as replacing existing lighting with energy efficient alternatives or creating partitions within the store, through to major changes, such as replacement of the refrigeration system with a modern, energy-efficient system. Through monitoring energy consumption, it may be possible to identify where the greatest opportunities for improving energy efficiency are.

Increasing the use of renewable energy for potato stores would allow a reduction in GHG emissions, and it is recommended that potato store managers explore the options available to them (Cunnington, 2019). The barrier to increased use is the challenge of matching the variable supply of electricity from wind and photo-voltaic generation with the variable energy demands of a potato store (Groves et al., 2011). Wind power may provide the best option for matching of demand to supply (Carbon Trust, n.d.). Ground-sink cooling provides a means of increasing refrigeration efficiency in potato stores (Pratt et al., 2009). Further efficiency is achieved if the warm water produced during the cooling process is used for heating (e.g. for grain drying).

In situations where large changes to the potato store could be of value, it is best to seek professional advice. For inefficient refrigeration systems, guidance may help to determine what the most cost-effective option is between maintaining the current system, upgrading it or replacing with a new system.

7. Protected Horticulture

7.1. Scoping exercise

The initial scoping exercise aimed to find broad reviews of greenhouse gas (GHG) emission reduction practices in the protected horticulture sector. Where glasshouses are heated with fossil fuels such as natural gas, this typically accounts for up to 90% of the GHG gas emissions. Therefore, much of the literature surrounding GHG emissions in protected horticulture revolves around reducing energy consumption from heating. Where glasshouses are not heated, the main emissions are again around energy use, although driven by electricity for irrigation, lighting, ventilation and other forms of climate control. This discussion around climate control is also relevant to heated glasshouses as heating is often tightly linked to the other aspects.

Gruda et al. (2019) provide a detailed comprehensive review of the impacts of protected horticulture on climate change with a broad range of mitigation strategies. They include detailed GHG emission analyses for a broad range of heated and unheated horticultural systems in several countries and climates. They provide a breakdown of emissions by source, such as fertiliser, irrigation, heating, substrate, glasshouse structure and product processing. The authors discuss in detail a comprehensive range of practices to reduce GHG emissions within the sector, including:

- Greenhouse insulation
- Thermal screens
- Novel glass coatings and fillings
- Dynamic climate control systems
- Cold-tolerant varieties
- Biogas
- Biomass
- Geothermal
- Solar panels
- Passive solar and closed/semi-closed glasshouses
- Novel glasshouse concepts such as 2SaveEnergy, ZINEG and VenLow
- Other practices around optimising productivity, reducing waste, and minimising impact of building materials

This information is supplemented with reviews by several different authors in a range of overlapping areas. Ahamed et al. (2019) provide a thorough comprehensive review of methods for reducing the heating cost of conventional greenhouses, including design and orientation, thermal screens, insulation, optimal climate control and a range of passive and active heat capture and storage options. Another review, by Sethi & Sharma (2008) provides additional detail on a comprehensive range of heat capture and storage technologies, while Cuce et al. (2016) review heat pumps, PCM storage, novel glass technologies and solar panels, amongst other practices. Biogas and biomass are reviewed by Dion et al. (2011), with an emphasis on CO_2 enrichment. Finally, Amani et al. (2020) provide a comprehensive review of ventilation, cooling, and humidity aspects of climate control, including a discussion of various types of passive and active dehumidification.

Additional practices were considered following discussion with ADAS technical experts in the sector and the AHDB. These practices include:

- North walls
- Underground thermal energy storage
- Water tank heat storage
- PCM heat storage
- CO_2 management
- Increased efficiency of product storage
- Supplementary lighting
- Alternative substrates
- Alternative packaging materials

All practices were then grouped according to common themes and a set of key practices were identified to take forward to REA, based on industry trends and feedback from technical experts (Figure 6).

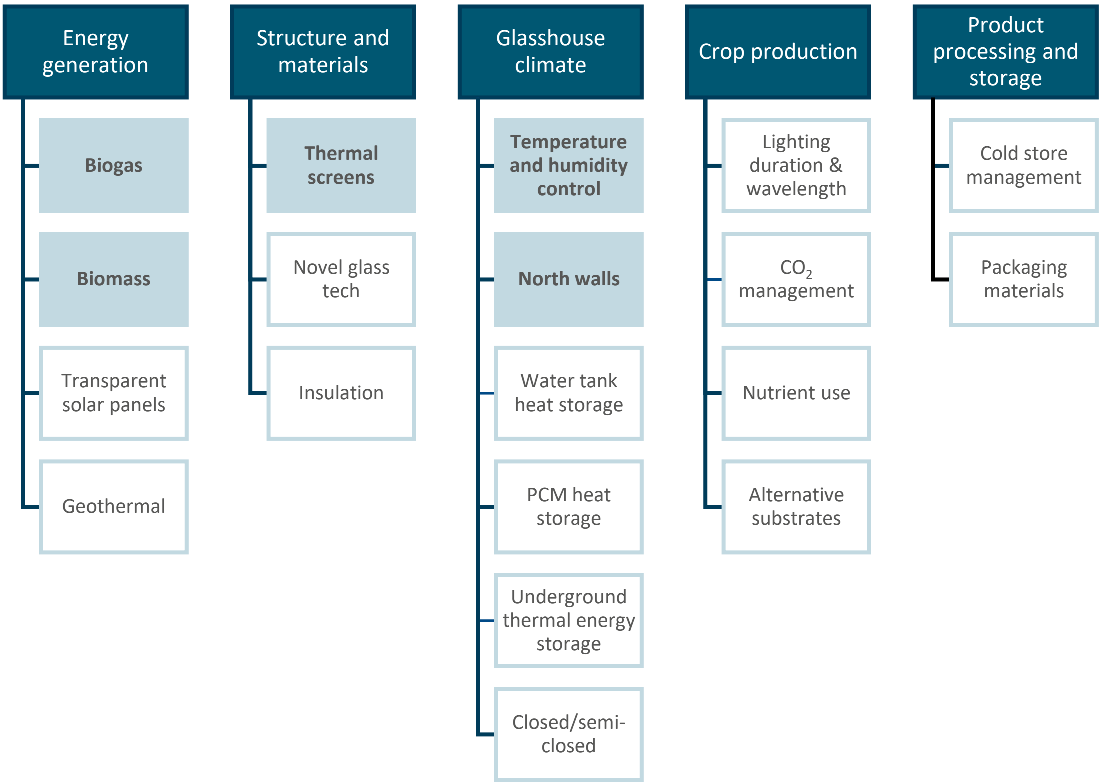

Figure **6**. Summary of main practices identified in the initial scoping exercise that may contribute to reducing GHG emissions in protected horticulture. Practices highlighted were chosen to be investigated further via rapid evidence assessment.

7.2. Critical review

The REA process enabled the creation of narrative summaries for several practices that have potential to reduce GHG emissions in the protected horticulture sector (Section 10.4). The evidence base for each practice is of varying quality and contextual relevance, and in almost all cases there are knowledge gaps to be explored further. Some of these knowledge gaps may be addressed through a broader and more thorough search process, while others may need additional experimental or contextual evidence. The narrative summaries have also highlighted issues that are common across multiple practices, suggesting a fundamental lack of knowledge or data across the sector. The following sections discuss these knowledge gaps at sector and practice level and suggest next steps to address them. Finally, those practices which were not progressed to REA are briefly summarised, highlighting where there is future potential.

7.2.1. Practices included in REAs

Biogas

In heated glasshouse operations, the combustion of fossil fuels for heating is by far the largest contributor to GHG emissions, typically accounting for 90-95% of emissions (Hospido et al., 2009). Biogas, which is predominantly comprised of methane, is produced during the anaerobic breakdown of organic matter and after light processing can be used in place of natural gas in boilers and CHP units (Gruda et al., 2019). Biogas can be produced via anaerobic digestion (AD) or via landfill and has much lower GHG emissions than natural gas. AD has historically been in the form of large-scale, centralised plants although farm-scale micro-AD is becoming increasingly feasible. By offsetting the use of grid electricity and fossil fuels such as natural gas and heating oil, biogas has the potential to greatly reduce GHG emissions, while still allowing crop CO_2 enrichment, but from a biogenic source rather than fossil source.

Switching from natural gas to biogas is a promising strategy to reduce GHG emissions in the heated horticulture sector. Biogas has a GHG emissions of 0.00021 kg CO_2e/kWh, which is much lower than natural gas (0.18387 kgCO_2e/kWh) and LPG heating oil (0.21448 kgCO_2e/kWh) (UK Gov, 2020). Where biogas is produced via anaerobic digestion, there are embedded emissions from the fertiliser and fuel used to grow, harvest and transport them. The extent of these embedded emissions depends on the source of the feedstock; for example, biogas produced using crop residues is likely to have lower embedded emissions than that produced from primary crops grown specifically for anaerobic digestion. While there is likely still a net reduction in GHG emissions compared to natural gas, the benefits are reduced compared to an AD plant that utilises waste products, and considering that land-use conflict with food production could offset emissions elsewhere, this approach is not preferable from a GHG perspective.

Whereas emission factors are provided for different types of combustion biomass fuels (e.g. wood chips, miscanthus), the government data does not distinguish between different types of AD feedstocks, so the exact GHG impact of different feedstocks is unclear (UK Gov, 2020). Going forward, it will be important to quantify the impact of different feedstocks from a GHG perspective, incorporating issues of land-use conflict as well as the different biogas yields from each feedstock.

AD is driven by living microorganisms which respond to changes in their environment, so consistency of feedstock is important to ensure consistent yield and composition of the resulting biogas, which is necessary for reliable operation of the CHP unit (Kothari et al., 2014). This creates a problem when using crop residues because the composition can change over the course of the year and there are seasonal peaks in feedstock availability. Therefore, it is likely that on-site AD will be best-suited (from a GHG perspective) to large growers with on-site packaging/processing that generate waste organic material all year round. Furthermore, the use of crop residues for biogas production competes with composting and other methods of improving soil organic matter.

AD plants are also subject to significant planning requirements and incur a cost of additional labour and maintenance. For some growers it may be more feasible to buy biogas from a centralised AD plant that is run using food waste, sewage sludge or other organic residues – although biogas is generally combusted on site to produce electricity and for it to be usable in horticulture it would have to be competitively priced with natural gas. Another option, which was piloted in France and has since been investigated in the UK, is the use of landfill biogas. This is produced in the anaerobic conditions inside landfills and is normally flared off, but Jaffrin et al. (2003) showed that this can be captured and used to provide heating and CO_2 enrichment in a research glasshouse, although purification of landfill biogas is challenging (Dion et al,. 2011). From the academic literature, it is clear that a transition to biogas is an effective way of reducing GHG emissions from protected horticulture, but questions still remain on whether it is economically viable and what method of production is best and most practical for most growers.

Biomass

Biomass fuels generally have very low levels of GHG emissions compared to fossil fuels (e.g. natural gas, 0.18387 kgCO_2e/kWh, or LPG, 0.21448 kgCO_2e/kWh) (UK Gov, 2020). Biomass boilers typically use wood pellets (0.01545 kgCO_2e/kWh), which are made from compressed sawdust (a by-product of the wood industry). In the UK the main alternative biomass sources are cereal or miscanthus straw (0.01629 kgCO_2e/kWh) or wood chips/logs from short rotation coppice or short rotation forestry (0.01545 kgCO_2e/kWh). The CO_2 produced during combustion of biomass crops is part of the biogenic carbon cycle – the CO_2 was captured during photosynthesis and then re-released during combustion with no net change in atmospheric CO_2 concentrations. Therefore, the only net emissions are those embedded in the growing, harvesting, transport and processing of the raw material. The source of the biomass has a role to play in further reducing emissions; aiming to utilise waste products, rather than crops specifically grown for biomass, helps to reducing the risk of unintended consequences, e.g. changes in land use elsewhere.

Most glasshouses that use natural gas for heating in the UK are also utilising the resultant CO_2 for crop enrichment, so for an alternative fuel to replace natural gas it is essential that it can provide this CO_2 enrichment as well. Biomass produces much higher levels of ash and other pollutants than natural gas or biogas and has faced more difficult technical challenges in developing a CO_2 utilisation pathway (Li et al., 2018). However, over recent years, these challenges have largely been overcome using a combination of physical and chemical purification methods (Dion et al., 2011). Sulphur dioxide (SO_2) is one of the main pollutants in biomass exhaust gas. It can be removed by passing the exhaust gas through an aqueous ammonia solution. This dissolves the SO_2 to form ammonium sulphate, which has applications as a fertiliser. The addition of cobalt and iodide ions can increase the removal of SO_2 and additionally remove nitrous oxides. An interesting additional area of research on biomass is around the generation of syngas (Dion et al., 2011). Biomass with a moisture content of 20-30% can undergo pyrolysis, which is heating at high temperature in the absence of oxygen, turning the biomass into a mixture of organic gases, liquid tar and oil and solid carbon (char). Next there is a partial combustion reaction that produces the heat to fuel a reduction reaction to create syngas – a mixture of hydrogen, carbon monoxide, carbon dioxide and methane. Syngas is used as a raw material in the production of industrial chemicals, fertilisers, fuels and other products and could represent a more cost-effective pathway for utilisation of biomass fuels.

North walls (passive heat storage)

North walls are an effective form of passive heat storage, consisting of an opaque wall built along the north side of the glasshouse. During the day, solar energy that would normally escape through the north side of the glasshouse is captured and stored in the wall material. At night, as the temperature drops, this thermal energy is released back into the glasshouse to increase the air temperature. Installation of a north wall can reduce heat energy use by 35-50% across a range of different glasshouse types and north wall materials.

Passive heat capture and storage is a method of capturing and storing heat energy on a diurnal basis, without the need for an external power source (Paksoy et al., 2015). In the northern hemisphere, glasshouses are typically aligned east-west to allow maximum sunlight from the south to reach the crops. This also means that a proportion of the light and heat energy escapes through the north side of the glasshouse. By building an opaque wall along the north side, heat is captured and stored during the day, and then automatically released at night as the temperature drops. North walls are typically made of bricks and/or concrete, and filled with water cannisters, sand, phase change material (PCM) or concrete (Berroug et al., 2011). North walls are generally insulated externally and can either be painted black on the south facing side to enhance thermal energy capture or can use reflective paint to increase reflectance of light onto the crop. North walls are often accompanied by a thermal screen during the night to minimise heat loss through the glasshouse roof and help ensure the heat released from the north wall stays in the glasshouse.

North walls are effective at maintaining an increased glasshouse temperature overnight (Sethi & Sharma, 2008). Ahamed et al. (2019) report heat energy reductions of 35-50% across a range of glasshouses implementing north walls made from bricks coated in concrete. Reducing energy use from heating will result in reduced GHG emissions from the burning of fossil fuels or grid electricity. In one case study from France, a 60cm north wall was constructed in a 30 m^2 tomato glasshouse alongside east and west side insulation. The system was able to meet 82% of annual heating needs (Berroug et al., 2011). Two other French studies, as reported by Ahamed et al. (2019), showed increased glasshouse temperatures of 7-9°C versus outside in both 100 m^2 and 340 m^2 sites. Berroug et al. (2011) showed that an 8 cm wall containing PCM had the same thermal performance as a 40 cm thick masonry wall, suggesting that PCM may be able to offer a more space-efficient wall design. Several authors have shown beneficial effects (up to 50% increase in illumination) of north walls painted with reflective material and inclined at 15° (Ahamed et al., 2019). In one case study, reported by Sethi & Sharma (2008), a reflective coating was painted on plywood above the north wall to reflect light towards the plants and floor. It was observed that the greenhouse required 14% less energy for heating during winter months as compared to a conventional greenhouse. Using aluminium sheets to reflect light and heat energy back into the glasshouse (rather than storing it) can also be effective at reducing heat requirements (Ahamed et al., 2019). One study used a 30 mm thick sheet of glass wool wrapped in airproof polyethylene film with aluminium coating and was able to reduce heating requirement by 28%, although electricity use increased by 35% due to additional supplementary lighting. Overall, there was a 25% energy reduction compared to a conventional glasshouse. Another study, from the UK, reported 20-25% higher internal light intensity from installing an aluminised polyester sheet along the north wall of a 120 m^2 glasshouse.

North walls will be most effective in small-scale glasshouses which are on an east-west axis. For large glasshouses, there is likely to be uneven redistribution of heat at night, which could result in quality differences across the crop. North walls should be considered in the context of other climate control practices being implemented, including active heating, ventilation and humidity control, as well as the crop type, the external climate and geography, and the size of the glasshouse. There are also many different materials, including bricks, concrete, sand, water and PCM. For non-PCM north walls, the minimum thickness should be 45-60 cm (Berroug et al. 2011), while the use of PCM can enable effective heat storage at just 8 cm, although with higher costs.

While there are multiple European case studies, there is a lack of contextual evidence in the UK to support these findings, particularly in terms of which glasshouse sizes, types and locations would benefit most from north walls. Additionally, there is no literature to date that has evaluated the overall impact on GHG emissions specifically.

Thermal screens

Thermal screens are installed on the inside of the glasshouse to form a false ceiling between the crops and the glasshouse roof. They are made from a variety of materials including aluminium, polyester and polyethylene. Thermal screens protect the crops from cold air falling from above while also preventing heat radiation from leaving through the roof of the glasshouse. The screens are typically installed on mechanical rollers so can be folded away during the day to allow increased light into the glasshouse. Thermal screens are a relatively cheap, highly effective method of increasing the average temperature inside the glasshouse, which in turn reduces heating requirements and energy use.

Thermal screens are widely used in crop management to manipulate temperature, light and humidity – in particular to prevent excess cooling which would affect plant transpiration. They are highly effective at reducing energy use with Dieleman & Hemming (2011) and Ahamed et al. (2019) both reporting at least 20% reductions in heat energy use across a range of European countries. One of the main evidence gaps in thermal screens is comparable evaluations of the broad range of different materials and installation systems, with accompanying contextual evidence through case studies. There is a considerable amount of literature on thermal screens, as they feature in most reviews discussing energy saving measures in protected horticulture. Given the diversity of thermal screen systems and the fast pace of technological development in materials, it may be worth bringing together the latest knowledge on thermal screens including how best to implement. When used optimally they are a highly effective and relatively cheap method of reducing energy use, and therefore GHG emissions.

Optimal climate control

One of the main benefits of protected horticulture is the ability to control the internal environment – particularly the temperature and humidity. The degree of control varies considerably, from solar heating with passive ventilation for cooling and dehumidification, to the use of advanced computer systems in closed greenhouses, which utilise real-time data from sensors to ensure optimal growing conditions. Optimising climate control is extremely important for maintaining crop productivity, reducing disease risk and minimising energy use. There are a range of techniques to do this, including increased use of sensors or automation, temperature integration and alternative dehumidification systems, all of which can complement other energy-saving practices.

Climate control inside the glasshouse incorporates several interacting elements: light, temperature, humidity and air circulation. Where CO_2 enrichment is used then it is also affected by the climate conditions. Climate control is complex because temperature, light and humidity are inter-related and changing one variable has consequences for the others. The use of automatic climate control that uses sensors to automatically adjust various settings to ensure optimal environmental conditions is likely to improve energy efficiency, although there is limited quantifiable evidence in the literature. The use of temperature integration, where the temperature is allowed to fluctuate over the course of the day while still maintaining a target 24-hour average, has been shown to reduce heating energy use by 30% in winter greenhouses in the Netherlands and France (Ahamed et al., 2019). Ventilation is a source of heat loss from glasshouses but is necessary for dehumidification, although systems have been developed to remove water from the air without external ventilation (Amani et al., 2020). There is one case study from Canada that shows success using heat pump dehumidification, but more contextual evidence is required for the UK – particularly its effectiveness in large-scale glasshouses. Another challenge in glasshouse climate control is in ensuring optimal air circulation to prevent dead zones; these are areas where temperature, humidity or CO_2 is not properly circulated, which have an increased risk of disease and poor crop performance (ADAS Horticulture Consultant, Pers Comm). Potential solutions include the use of fans linked with more advanced sensors, such as infrared cameras, but these options have yet to be investigated academically.

7.2.2. Sector-wide evidence gaps

Variability in production systems

One of the main challenges in evaluating the evidence base for GHG-reducing practices in protected horticulture is the variation in growing systems. The crops grown, scale of production, precision of climate control, level of automation, type of substrate and, above all, heating use vary significantly across the sector, with different practices applying to different systems. Even within a practice, there may be a broad range of implementations that can be adjusted based on the system. With so many production systems and such a broad range of implementation types, it is difficult to generalise on the effectiveness of many techniques.

Lack of relevant context/case studies

Many of the narrative summaries were restricted in the availability of detailed, UK grower-level data. The effectiveness (and economic viability) of most practices will vary depending on the type and size of production site, as well as the specific format of the practice being implemented. The use of reviews is an effective way of determining the average impact of a practice across a range of different contexts, but for implementation on a practical level, growers need more contextual information than is available in the evidence base. Much of the information on costs and best practice are taken from case studies in the Netherlands. There are excellent examples of innovation across the UK protected horticulture sector in individual businesses, but best practice needs to be shared. As such, knowledge sharing should be a key theme going forward.

7.2.3. Additional practices and future developments

There were a number of other practices that were screened at the initial stages of this REA process, but insufficient evidence was found to take through the entire REA process. These practices are summarised below, with a brief description of the practice and discussion on future applications where appropriate.

Geothermal

Geothermal has future potential but is currently too expensive to be set up on a single site. Future government incentives might make the investment more feasible. Other considerations include regulations and licensing, as well as the underlying site geography.

Water tank heat storage

In the UK, one of the most common forms of heat capture and storage is the use of large water tanks to store excess energy from combined heat and power (CHP) boilers. This is a form of active storage, where electric heat pumps are used to actively transfer heat from a source (e.g. CHP boiler) to a store (e.g. water tank) (Paksoy et al., 2015). Many large glasshouses combust fuel (normally natural gas) during the day to produce CO_2 for crop enrichment which also generates heat energy. In the winter this heat can be used for glasshouse heating but in summer heat is only required at night, creating a mismatch between heat production and requirement. This excess heat can be transferred into a storage medium and then released again at night when the temperature starts to fall. Large water tanks are a cost-effective way of achieving this. Water tank heat storage is commonplace wherever CO_2 enrichment is used, and it seems likely that the GHG emission reduction from reduced heating fuel use will more than compensate for the additional electricity required to operate the heat pump. However, there were no studies in the reviewed literature that directly quantified the GHG emission impacts of active water tank heat storage systems. Other forms of active heat storage include PCM storage and underground thermal energy storage (UTES).

Underground thermal energy storage (UTES)

The main types of UTES are aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and cavern thermal energy storage (CTES), although ATES and BTES are the most common. All systems are active seasonal heat storage solutions, allowing summer heat to be stored underground in water (ATES and CTES) or rock (BTES) and then retrieved in the winter using heat pumps. As with geothermal, the main issues are high costs, site geographical suitability, and extensive planning and regulations. For underground storage, Paksoy et al. (2015) found 20-

30% total energy savings following installation of aquifer thermal energy storage system with a heat pump in the Netherlands. There is a lack of case studies for underground thermal energy storage solutions in the UK, which restricts the ability to determine costs and best implementation.

Phase change material (PCM) heat storage

PCM heat storage uses various chemicals (often petroleum derivatives or salt hydrates) that release and absorb substantial amounts of energy during phase transition, i.e. from solid to liquid. PCM storage can be passive, working in a similar way to north walls, or can be active, working in a similar way to water tank storage. PCM storage is more expensive to install than alternative methods, although it requires less space so may be favourable where space is limited. PCM materials include salt hydrates, paraffins and polyethylene glycol (Kürklü, 1998). Paksoy et al. (2015) reviewed three French glasshouses incorporating PCM systems and reported 20-50% total energy savings in passive and active systems.

Dehumidification heat pumps

One potential application of heat pumps is in extracting heat from air during dehumidification and/or ventilation (Amani et al., 2020). This energy could then be stored and released when heat is required. Energy capture from dehumidification systems have shown promise in other countries but there is no evidence in the UK context (Amani et al., 2020). There are also challenges around scaling the technology to large, open-plan glasshouses, and potential zones of high humidity surrounding heat pumps which could promote disease.

Solar panels

There are range of solar panel technologies in development. Translucent PV may have potential in the future depending on the amount of light interception. There are also likely to be implications around cost and maintenance.

Next generation cultivation

These concepts are being developed in the Netherlands and consist of glasshouses that have little to no external ventilation, controlling temperature and humidity through heat capture and storage, and dehumidification systems. Specific projects include the VenLowEnergy greenhouse, 2SaveEnergy greenhouse and ZINEG greenhouse.

Lighting

There is still a room for development around LED technology, including optimising wavelengths and the arrangement of light around and between the crop canopy, as well as opportunity for more advanced reflectors.

Energy efficiency audits

Energy is typically the main cost and source of GHG emissions in protected horticulture, so the implementation of regular energy audits to highlight key sources of energy use are likely to be beneficial. Simple solutions like heat pipe and boiler insulation, and repairing gaps between panes and doors can also have small benefits.

Product storage

This can be a significant source of energy and GHG emissions in the production of several UK crops. A general overview of cold storage can be found in the potato section of this report.

Novel glass technology

There are a wide range of interesting novel glass technologies in development including double glass with layers of vacuum, aerogel, argon, or phase change materials in between, and coatings that trap light inside the glasshouse and ensure diffusion through the crop.

Efficient CO_2 management

Currently there are issues with time reactivity of CO_2 dosing systems. Development of technologies to monitor and regulate CO_2 more quickly and accurately could have benefits. With likely future development of carbon capture and storage technology, there could potentially be opportunities for the protected horticulture sector in the form of novel CO_2 sources.

8. Discussion

Do these practices reduce GHG emissions from the relevant sectors?

The aim of this project was to evaluate the evidence base for Net Zero practices (i.e. practices that can lead to reductions in GHG emissions or increase carbon sequestration) in the pork, potato and protected horticulture sectors using the EFI evidence standards. A wide range of options for reducing GHG emissions in each sector were identified, with varying degrees of effectiveness, applicability and validity. The REA process then focused on those for which there was the most evidence or for which there was greatest interest from within the sectors to learn more. To avoid repetition, practices that were relevant to these sectors, but already included within REAs completed for either Cereals and Oilseed or Dairy were excluded.

In the **pork sector**, the embedded emissions in the feed are the major source of emissions from production, but it is largely out of the pig farmers' hands to influence the emissions intensity of their feed. Reducing emissions from the raw materials used in feeds is captured within the AHDB arable rapid evidence assessment (Stockdale & Eory, 2020). The main influence that the pig farmers have on feed is the quantity fed and therefore the review focused on the development of total productive maintenance (TPM) approaches, specifically precision feeding. Manure management is another key source of emissions. Some aspects of manure management were captured within the AHDB dairy rapid evidence assessment (Gill et al., 2020). This left the focus for the pork REAs on slurry cooling, micro anaerobic digestion (AD) and hydrogen electrolysis. The final area of focus was emissions from housing and use of scrubbers to clean exhaust gases.

Good levels of evidence were found for most of these activities with a number of reviews and syntheses available for most of these subject areas. The academic literature used as the basis of the reviews often focused on the practices delivering alternative goals such as reductions in feed consumption and reductions in ammonia emissions or odour control, with GHG emissions only considered as a secondary part of the assessment if at all. It was therefore not always possible to provide quantification of the GHG emission savings, although it was in most cases possible to determine if a positive or negative effect would be anticipated. It would be possible in most cases to use some of the information presented in the reviews to calculate an emissions reduction (e.g. switch from natural gas to biogas from micro-AD), but that additional analysis was outside of the scope of this REA process.

Much of the evidence base used for the reviews and syntheses came from studies that were conducted in the Netherlands or Denmark, where strict regulation and high densities of pig production have driven investment in research. Not all of their production systems are directly comparable to UK production systems, e.g. higher proportion of production on slats compared to straw filled barns, and therefore the evidence for UK based applications of the practices is reduced.

In the **potato sector**, the key sources of emissions are nitrogen application (well covered in Stockdale & Eory, 2020) and energy use for both the cultivation, planting and harvesting of the crop and also for the storage of the crop post-harvest. The REAs in this project therefore focused on improved energy efficiency in cultivation and storage. More specifically the searches focused on reduced cultivation intensity, improved insulation of stores and reducing air leakage in stores. An initial search of the literature resulted in no reviews or syntheses being found on any of these subjects, with little in the way of academic literature focused on improving energy efficiency. Instead an adjustment was made to the review approach to include some aspects of grey literature.

The majority of the literature that is available has been generated by AHDB-funded projects, few of which have had associated peer reviewed papers published from them. This does not necessarily mean that the scientific approaches and methodologies applied are any less robust than those applied in academic publications, just that no paper was funded out of the project.

The nature of the practices reviewed meant that most of the information that was available on the practices focused on improvements in energy efficiency, and impact on yield or quality. Few of the studies had directly translated the energy savings, yield benefits or quality improvements into GHG emissions savings. It was beyond the scope of this review to perform these calculations, however, a sound understanding of emissions sources and relative emissions intensities of fossil fuels and grid electricity clearly showed that any reductions in use of either diesel or grid electricity will have both a financial benefit to the farm and reduce GHG emissions. However, the scale of reduction possible is going to be highly variable dependent on the initial level of efficiency and resultant efficiency.

There is limited ‘current’ data on the performance of potato stores across the UK, and the proportion of stores that have different features including thickness of insulation, type of management system or efficiency of refrigeration unit. The recent studies conducted by Swain (2010) and Swain et al. (2013) found many stores with poor energy efficiency; however, it is unknown how much investment has taken place in the years since these assessments were made. Without this baseline understanding of the level of existing uptake of these practices it is not possible to determine the level of impact that these types of practices could have at a national scale in the current time.

In the **protected horticulture sector,** the key source of emissions is from energy consumption, either from fuels that are burnt to produce heat, or electricity that is used in ventilation and lighting. Therefore, as for potatoes the key focus of practices reviewed in this REA was in reducing energy use and improving energy efficiency. Practices considered included production and use of biogas for heating, use of biomass and north walls to reduce emissions from fuel combustion, and the use of thermal screens and optimal climate control to reduce total energy requirement.

There was a reasonable level of evidence available for these practices, with a number of reviews and syntheses found within the academic literature. However, as the main drivers in many horticultural systems are reductions in cost of production as well as improvements in yield and/or quality, these tended to be the focus of many of the reviews, rather than the GHG emissions reductions achieved. The practices reviewed clearly identified that there are options out there for reducing the need for fossil fuels in heating and powering protected horticultural crops, however, the more high tech options such as biogas and biomass to a certain extent are still very much in the development stages, with the technology rarely having been tested on farm. Thermal screens are already widely used, and therefore the level of additional uptake possible may be limited. Within heat capture and storage, active water tank storage is already widely in place, and although north walls may be suitable for small-scale growers, there is a lack of evidence in the UK context – which is particularly important when the effects are driven by sunlight and temperature.

The practices selected for REAs that are presented for these sectors are not necessarily the best or only options that are available for the sector, with some important practices already having been covered in Stockton & Eory (2020) and Gill et al. (2020). It is also important to realise that for something like improving energy efficiency, as is the focus for both the potato and protected horticulture sectors, it often requires a holistic view of the entire store or glasshouse system to identify where the most cost-effective energy reduction approaches can be applied. The approach will be very different if retrofitting existing infrastructure as compared to building new structures. The REAs can therefore provide farmers and growers with ideas of key areas to focus on when considering retrofitting, or constructing new infrastructure, but expert advice and specific analysis of baseline vs forecast performance would be needed to demonstrate the scale of net emissions reductions and also cost of implementation.

Improving the quality of the data, particularly on costs and return on investment, will be required to encourage uptake of these practices. Much of the data presented for the practices within these REAs is from case studies rather than controlled experiments, because of the nature of these practices (e.g. large-scale infrastructure). This is in contrast to the practices presented in Stockdale & Eory (2020) where they were able to draw on evidence syntheses that aggregated many individual experiments, because they were focusing on practices that are more around behaviour or management change rather than large infrastructure. In addition, for the pork and protected horticulture sectors there was a lack of UK-context in much of the evidence base, with many of the case studies from mainland Europe. The information is there about how the practices work and what they can do, but the applicability to UK production systems has rarely been assessed within the published literature.

An additional aim of the project was to identify practices that have potential for Net Zero benefits but currently do not have a sufficient evidence base for the inclusion in the narrative summaries. These practices are potential areas for future work, and brief summaries have been provided. They include new approaches to slurry management and storage in pig units, reducing emissions from straw-based pig production systems, improvements in productivity (across all systems) and a wider range of options for improving energy efficiency whether in pig housing, potato storage or glasshouse management.

In many cases it is important to not just look at a practice in isolation, but to consider its impacts within a holistic view of the production system. For example, improving energy efficiency or total productive maintenance are not single activities, they require an interaction of multiple changes in practice to deliver the optimal performance for an individual farmer.

Feedback

One key objective of this process was to provide feedback on AHDB's 'organising framework for evidence' and 'generation and application of evidence standards' working drafts.

The process for collecting evidence for the EFI is designed to provide AHDB with a robust evidence base to support farmer decision making on practices to improve farm performance, with an initial focus on moving towards Net Zero. Collection of data through a rapid evidence assessment with presentation of the collated results in a user-friendly narrative summary aims to rapidly collect a large body of evidence and distil it into a clear and simple format for use by the farmer. In general, the EFI process provided an effective standardised framework to assess actionable practices for reducing GHG emissions. However, in conducting this project, strengths and limitations have been identified in this process.

Defining the question: We started with a simple question of '*Does [practice] reduce GHG emissions in sector X?*'. This gave a clear focus and addressed the question set out in the research brief. However, the literature for the specific practices did not always focus on their impacts on GHG emissions, with primary focuses tending to be ammonia reduction (pork) or energy efficiency (potatoes and protected horticulture). Therefore, it was not always possible to directly assess the answer to this question, and often impacts had to be inferred based on the wider information given within the syntheses.

Defining the practices: The scope of this REA meant that we focused on a small number of key practices, avoiding overlap with previous REAs. We aimed to tightly define specific practices – e.g. an actual technology or activity – rather than having a broad practice of ‘improving energy efficiency’. This in most cases allowed for specific analyses to be completed and assessed within the framework. However, many of these individual practices are part of a holistic management system, and therefore scale of impact depends on the wider context on-farm.

Most of the practices selected in the pork sector were new technologies that could be introduced to the sector. As a result, much of the information on these practices lacked commercial UK context, meaning that information on practical implementation was limited. In the potato and protected horticulture sectors there were more ‘best practice’ activities found, such as increasing insulation thickness or use of thermal screens. In the case of these, the level of impact of implementation depends on where the farm’s starting point is – the benefits in a poorly managed or maintained older store or glasshouse will be greater than implementation in a modern, well-managed equivalent. For other practices such as micro-AD, biomass boilers or heat capture and storage, the theory shows that they can have a positive impact on reducing emissions, but there are practical challenges to the implementation on farm that have yet to be reviewed within the literature. Additionally, many practices had different variations of implementation that occasionally resulted in different impacts. For example, air scrubbing uses three main systems, often in combination, although it was found that the likely GHG impact was different for each one, with some appearing to increase emissions.

The framework: For most assessed practices this was an effective way of quantifying the key elements of effectiveness, cost, speed of change and strength of evidence. By using the same metrics for each practice, this allows users to quickly compare practices and potentially identify which practices to explore further. It is important that the reader makes sure that they understand what the scores mean by checking the criteria as the simplicity of the scales also leads to the potential for the reader to ‘interpret’ as they see fit. In creating metrics that allow comparison between such a diverse set of practices there will be challenges in setting values.

Some of these practices show high levels of variability in their effectiveness and costs. Sometimes there was too much variation even within a tightly defined practice to make useful summaries e.g. air scrubbers. Where reviewing these there were three different technologies that were identified through the literature. They have a primary focus of reducing ammonia emissions and odour, which they all deliver, but their impact on other gases is more variable, e.g. some clearly increase N_2O

emissions, whilst others have the potential to reduce N_2O emissions, so in reality they each would have been best reviewed separately. Because the focus of the research into these scrubbers was predominantly ammonia the detail of impact on GHG emissions was not always clearly captured in the studies, and where it was it was rarely looked at in a holistic way, e.g. considering impact on N_2O, methane and indirect emissions from ammonia deposition. This meant that the evidence base for these technologies was not complete with regards their impact on Net Zero.

What the framework was not able to do was to capture the site-specific elements of some of the practices. Although the narrative summary did state where the practice would work, it was often not possible to provide clarity on where it would be most appropriate to use it.

Effectiveness: The approach taken in the methodology is to score the quality of the evidence for a positive or negative effect on a parameter (e.g. GHG emissions). The use of a scoring system for things like the GHG impacts was helpful, especially where studies did not fully quantify effects, as it gave an indication of a direction of travel. However, it is not possible to determine from the scoring system the scale of change. For example, repairing leaks in a potato store may consistently demonstrate a positive reduction in GHG emissions so gets a ++ (see appendices for scoring structure), but that does not necessarily mean it reduces emissions more than a practice that scores +, it is just that the strength of evidence is greater for the first practice. It can also be seen from these scores, where additional areas such as ammonia emissions are included, where the focus of the evidence base actually is.

Cost: This approach basically identified the scale of additional costs over and above business as usual (BAU), e.g. requires time invested in training and learning, some equipment and capital costs or major investment in new infrastructure. The range in practices that were covered within this REA process meant that it is not always possible to compare directly between two practices. E.g. how do you compare the cost of investing in new insulation for a potato store to investment in a biomass boiler, they might both score a £££ for some equipment and capital costs, but the scale of cost is different. To identify actual costs of implementation a different approach to identifying data sources would be needed as these are likely to come either from specific case studies or from commercial sources, certainly in the case of equipment and infrastructure costs.

Speed of change: While a measure of speed of implementation is useful for farmers, this is rarely described in the literature, it is therefore more of an expert perspective created by the reviewer. The majority of the practices that were included in these REAs required investments in technologies, some are available now, but would likely take at least 12 months to implement, and some have a much longer time horizon as the technology is either in development, or not widely used and implemented within the UK. This means that having ‘slow’ as anything over 12 months is oversimplifying the timescales for some of these investments. Separating that category into 1-2 years and 2-5 years might help to make that distinction between the projects that can start now but will take time to implement and those that are waiting for technologies to become available.

Strength of evidence: The framework for assessing strength of evidence and its relevance to the farmer audience is also generally effective. It favours evidence reviews, which are predominantly focused on the academic literature. This means that some of the useful information that is captured within the grey literature, such as research conducted for AHDB or Defra, is not readily captured within the reviews. This approach is potentially useful in situations where a practice and research base has been around for a long time, such as many of the nutrient management practices. However, it does have its limitations where new technologies are being developed, as it takes time to build a sufficient wealth of evidence to make a review practical. It is also less practical to apply where the main driver for improvement is business profitability (e.g. some of the energy efficiency work) which tends to evolve as commercial improvements to technology and incremental improvements to efficiency with each new product release. This is potentially the case for some of the activities relating to improving the efficiencies of potato stores and glasshouses, where there is information available, but it is not within the academic literature.

It is worth noting that there is often a trade-off between context and quality, with higher quality reviews tending to seek a broad, general audience, whereas context is more likely to be delivered in more targeted papers. It is therefore important to isolate the quality of the evidence (in terms of robust methods and accurate data), as well as the context that the evidence was generated in (commercial farm, research, etc.). The EFI process was also most effective when there were several quality review papers in the academic literature. Where this was not the case, the framework was more restrictive in its ability to bring in other evidence, e.g. from industry and grey literature.

Improving the usefulness of the process

The target of the REAs are syntheses where evidence from multiple sources has been collated and evaluated. This process allows relevant, robust data to be quickly identified. In the pork and protected horticulture sectors, a small number of relevant syntheses were found, whereas for the potato sector no syntheses were found. By focusing on syntheses, the REA process aims to maintain a high level of robustness. This approach is likely to be highly relevant to practices where there is a wealth of evidence and numerous reviews and syntheses have been completed, but as you start to more away from practices that have been the focus of large research efforts (e.g. around reducing nitrate or ammonia pollution) and the types of practices move towards improvements in productivity and efficiency, the evidence base it not always as well reflected within the academic literature.

Identifying relevant literature: The protocol developed for the searches of the academic literature did identify relevant grey literature (when used searching via Google). However, the REA approach for reviewing this type of literature is more challenging as the titles are less structured and descriptive, and they do not necessarily have abstracts. The structure of academic literature on literature review sites, such as Google Scholar or Science Direct makes for easy extraction of key information and cross linking to other related studies. The grey literature is not catalogued in the same way and finding the data sources and related data sources is therefore more time consuming. Therefore, inclusion of this type of literature in the review process is more time consuming and not suited to a short turnaround REA approach. However, there is a wealth of information in, for example, Defra or AHDB reports that is often UK specific and more applied in nature than some of the research projects included in the academic literature, so by excluding this type of information from the process important evidence may be missed.

Relevance of context was challenging to implement from many of the syntheses as it is often difficult to determine whether a practice was “applied by professional researchers” or “with farmers and growers testing the practice”. It may be more relevant to define whether the evidence is from modelling, laboratory, research centre or commercial farm.

One important consideration is how practical the evidence is. What may demonstrate benefits under experimental conditions may not show the same level of benefits on-farm or may not be practical. In discussing with sector experts, some of the practices described in the literature as feasible are not being used on-farm because of various barriers, including several of those identified in the scoping exercise. For example, reduction of crude protein in the diet is widely referenced in the academic literature, but industry knowledge suggests it is only feasible in mixed-sex systems which are impractical for most farms. Several of the practices that were identified in the scoping exercise were not progressed because of that reason. It could be argued that a resource such as the Potato Store Manager’s Guide (Cunnington, 2019), which is based on many years of experience and a significant body of research (both published and unpublished), provides more valuable practical evidence than academic syntheses which may not have actually tested the practice on farm.

In addition to the grey literature there are many of the developments around improving efficiency in various aspects of production that are being driven by the industry itself. Some of this implementation is captured in case studies, but these are just single examples and do not represent a robust evidence base, however they may provide additional useful insight into actual implementation. When changes are being made on-farm (e.g. an upgrade of a potato store) it provides an opportunity for collecting data and producing a case study; the lack of available case studies shows that incentives for doing this are insufficient. Incentivising the sharing of this data would strengthen the evidence base to facilitate decision making with regards to implementing new practices.

Inclusion of the grey literature and industry examples within the evidence base is unlikely to be practical within the timescales and structure of an REA process. Greater time would be needed for screening the literature and then determining its appropriateness for inclusion.

Recommendations

The EFI platform is aiming to provide a robust evidence base of different practices. The REA process and framework allow a consistent approach to the inclusion of information within the platform. However, as discussed above there is potentially a volume of valuable literature that is not captured within the process. The literature is likely to be particularly important around demonstration of practical implementation of actions. In order to support the evidence base, we would suggest that the EFI also aims to capture one or more relevant case studies for each practice. The data on “how to do it well” and “how much does it cost” are too vague from the literature, but when the evidence from the literature is used in combination with a practical example it will help to bring the practice alive for the farmer by helping to provide answers to those questions within a specific context. Ideally the approach would also be supplemented by additional grey literature from more applied research projects to help provide clearer answers to the more practical questions of “does it work in practice”, “how much does it cost”, and “how can I do it well”?

We would suggest that the REA process is a good starting point, but where evidence gaps or uncertainties remain in the evidence base that could be addressed through the use of grey literature or industry sources, a secondary step is included after the initial REA to aim to fill those gaps.

At present the mechanism for looking at cross synergies between practices – e.g. the wider environmental or economic benefits – is not well defined. This means the author can define their own ‘wider benefits’, which may make comparison between REA narrative summaries more challenging. Developing a structure for the other wider benefits, such as impact on ammonia emissions, would allow for consistency of reporting and allow greater read across the narrative summaries.

It was only possible to complete a selected number of REAs within the timescale of the project and therefore there are potential opportunities to increase the number of REAs completed in these sectors, e.g. additional REAs on total productive gain. A number of evidence gaps have been identified, some of which require more detailed review processes to complete, others actually require new data to be produced. These potentially offer AHDB with opportunities for future research projects and could be included in any future planning for new work.

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10. Appendices

10.1. Evidence for Farming Initiative (EFI) Draft Evidence Standards

10.1.1. Effectiveness

-ve	**Evidence tends to show a negative effect.** The balance of evidence (including the pooled effect size where available) suggests that the practice has a negative effect, meaning the practice made things worse. This takes into consideration the number of studies showing positive and negative effects, and the levels of involvement (number and size of participating entities) in those studies.
0	**No effect.** The balance of evidence (including the pooled effect size where available) suggests that the practice has no effect overall.
+/-	**Evidence tends to show a mixed effect.** Studies show a mixture of effects and the criteria for 'tends to negative effect' or 'tends to positive effect' are not met.
+	**Evidence tends to show positive effect.** The balance of evidence (including the pooled effect size where available) suggests that the practice has a positive effect. This takes into consideration the number of studies showing positive and negative effects, and the levels of involvement in those studies.
++	**Evidence shows consistently positive effect.** The evidence (including the pooled effect size where available) consistently suggests that the practice has a positive effect. This takes into consideration the number of studies showing positive and negative effects, and the levels of involvement in those studies.

10.1.2. Cost

£	No new equipment or time constraints over and above existing business as usual (BAU) running costs.
££	May need some additional time for training or experiential learning to establish new practice, but once implemented this rapidly transitions into BAU running costs.
£££	As above, plus new equipment and capital costs for machinery and implements on farm.
££££	Major investment in new infrastructure on farm and/or loss of land utility/land use change that is greater than the normal rotation(s).

10.1.3. Speed of change

Fast	Effective immediately, change within 0-3 months.
Moderate	Effective within 12 months.
Slow	Effective in longer than 12 months.

10.1.4. Strength of evidence

	Very high	High	Moderate	Low	Very low
	●●●●●	●●●●○	●●●○○	●●○○○	●○○○○
Quality of literature	An extensive body of high-quality evidence reviews.	A developing body of high-quality evidence reviews.	Studies of the highest quality (randomised control trial equivalent) OR at least one high-quality evidence review.	Studies using quasi-experimental methods OR at least one moderate-quality evidence review.	High quality observational studies.
Relevance of context	As level 4, but with excellent contextual and Implementation insight drawn from high-quality studies and on-farm practice.	Includes evidence generated in farming and growing businesses with farmers and growers testing the practice.	Evidence generated in farming and growing businesses with the practice applied by professional researchers.	Evidence generated in research centre farming and growing facilities.	Evidence generated through laboratory research.
Overall	We can draw very strong conclusions about impact and be highly confident that the practice does/does not have the effect anticipated. The body of evidence is very diverse and highly credible, with the findings convincing and stable.	We can draw strong conclusions about impact and be confident that the practice does/does not have the effect anticipated. The body of evidence is diverse and credible, with the findings convincing and stable.	We can draw some conclusions about impact and have moderate confidence that the practice does/does not have the effect anticipated. The design of the research allows contextual factors to be controlled for.	We believe that the practice may/may not have the effect anticipated. The body of evidence displays significant shortcomings. There are reasons to think that contextual differences may substantially affect practice outcomes.	The body of evidence displays very significant shortcomings. There are multiple reasons to think that contextual differences may unpredictably and substantially affect practice outcomes.

10.2. Pork

10.2.1. Slurry cooling

Impact summary

Slurry cooling involves pumping cold water through a series of pipes within or under the stored slurry. This draws heat from the slurry, reducing its temperature from 30-35°C to 10-12°C. The reduction in temperature reduces the activity of microbes in the slurry, resulting in a decrease in ammonia and methane production. Ammonia, while not a GHG itself, is associated with increased emissions of nitrous oxide in the environment, so reducing ammonia can have indirect benefits for N_2O. Reducing ammonia also improves air quality which can result in lower electricity use for ventilation. By using a heat exchanger, the extracted heat can be used for heating sheds or farrowing areas. A reduction in the use of grid electricity or fossil fuels for heating has additional benefits for reducing GHG emissions.

Effectiveness		
	Reduced net GHG	+
	Other impacts	
	Ammonia reduction	++
	Heat generation	++
	Improved air quality	++
	Reduced odour	+
	Reduced energy use	+
Cost		
		£££
Speed of change		
		Moderate
Strength of evidence		
	Quality	2
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

Slurry cooling involves lowering the temperature of stored slurry from 30-35°C to 10-12°. Slurry cooling reduces methane and ammonia emissions by slowing the activity of microorganisms, which are more active at higher temperatures. Cooling is achieved by circulating cold water through pipes or fins which are in close contact with the slurry, drawing heat from the slurry into the water. The water is then put through a heat pump to produce low grade heat (35-50°C) for heating sheds, farrowing pads, or stored water. Slurry cooling can be installed in new-build pig units by laying the pipes directly into the concrete base of the slurry store. It can also be retrofitted by installing raised pipes to the base of existing slurry stores (provided there is enough depth) or take the form of floating fins (heat exchangers) that rest on the surface of the slurry.

2. How effective is it?

Slurry cooling has widely been shown to reduce ammonia emissions during in-house slurry storage, which can indirectly reduce N_2O emissions because some of the nitrogen in deposited ammonia is nitrified into N_2O in the environment (Zhu et al., 2013). Botermans et al. (2010) reported ammonia reductions of 30-50% across four installations in Denmark and the Netherlands. Mazur et al. (2019) found a 31% reduction in ammonia evaporation within slatted housing using in-floor slurry cooling and a 60% reduction in ammonia evaporation during subsequent field application. They also suggest a reduction in methane and CO_2 emissions, but don't provide figures. Hilhorst et al. (2002) observed a 30-50% reduction in methane emissions using floating heat exchangers. Several studies have found that slurry cooling also reduces the need for cooling fans and ventilation, although don't provide quantification. Where slurry cooling is used for heating, this will offset fossil fuels or grid electricity, which will have additional benefits in reducing CO_2 emissions, although the reduction will depend on the exact implementation.

3. Where does it work?

Slurry cooling is only possible in fully or partially slatted units with a shallow slurry store (Santonja et al., 2017). It is most effective when installed into the concrete of new-build units and coupled with heat pumps (AHDB, 2019a). Slurry cooling is best suited to operations with nearby heat requirements, such as in farrow-to-finish units which require heating for the piglets. Retrofitting is possible by installing pipes above the floor, although technical issues, such as difficulty cleaning under the pipes between production cycles, often makes it uneconomical (AHDB, 2019a). The only retrofitting option that is recognised as BAT is the use of floating heat exchangers, although these also have issues such as crust formation and freezing (Santonja et al., 2017).

4. How much does it cost?

There is a lack of accurate cost information in the UK context, although evidence from across Europe suggests a ROI of less than 5 years. Mazur et al. (2019) suggest costs of £24 per pig place for an in-floor system in a farrowing unit in Denmark, with a ROI of 2-5 years. Santonja et al. (2017) suggest installation costs of £23 and annual operating costs of £4 per pig place for floating heat exchangers in a partly slatted finishing pig unit. There were no figures available to determine the value of electricity savings. Previously slurry cooling with heat exchange would have been supported by the renewable heat incentive (RHI), a government scheme that paid producers a fee per kWh of heat produced from renewable heat sources. The scheme ended in March 2021 and it is unclear what form any future support might take. The cost-effectiveness of slurry cooling in the UK is likely to depend on the availability of such schemes in the future.

5. How can I do it well?

Slurry cooling is most suitable for new-build operations with a requirement for low-grade heat near to the slurry storage area, such as a farrowing unit. There are several technical considerations such as the layout and spacing of the pipes, the capacity of the heat pump, the coolant temperature settings and applications for generated heat. AHDB (2019a) recommend involving an approved heat pump installer and obtaining a full specification of the installation and evidence of correct installation for the underfloor elements of the system. The area of slurry cooling depends on the scale and types of production, as well as the heating requirements. Small additional savings can be realised by running the heat pump with renewable electricity supplied by e.g. solar panels.

6. How strong is the evidence?

Multiple reviews have consistently reported at least 30% reduction in ammonia emissions from in-house slurry storage across a range of systems. Some ammonia is ultimately nitrified into nitrous oxide in the environment, so this is likely to have a beneficial effect on GHG, provided mitigation measures are put in place during application. One review found a 30-50% reduction in methane emissions, although further evidence is needed to verify this. There was also one review that suggested additional reduction of ammonia during spreading, although that is another area that needs to be more fully investigated.

7. Where can I find further information?

Additional information is available in the best available techniques (BAT) reference document for intensive rearing of poultry or pigs: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/best-available-techniques-bat-reference-document-intensive-rearing-poultry-or-pigs

AHDB provide practical information on the impacts of slurry cooling and advice for implementation: https://projectblue.blob.core.windows.net/media/Default/Pork/Documents/SlurryCoolingGuide1939_190704_WEB.pdf

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4. Santonja, G. G., Georgitzikis, K., Scalet, B. M., Montobbio, P., Roudier, S. & Sancho, L. D. (2017) Best available techniques (BAT) reference document for the intensive rearing of poultry or pigs. *EUR 28674 EN*.

1. Descriptive literature review of all practices that can mitigate ammonia emissions, primarily within the Swedish context. Describes slurry cooling systems in a research farm in Sweden and a commercial farm in the Netherlands, with associated NH_3 emission reductions.

2. Descriptive literature review of ammonia reduction practices associated with manure management in indoor pig production systems. Brief overview of different methods of slurry cooling with associated ammonia reduction impacts, as well as figures for typical installations in Denmark.

3. Brief descriptive review of methane-reducing practices associated with manure management in Dutch livestock production. Description of a floating cooling system on a Dutch pig farm with effect on methane and ammonia production over the course of a year.

4. Reference document for the best available techniques in intensive pig and poultry production. Provides information on slurry cooling installation and an overview of costs.

10.2.2. Air scrubbing

Impact summary

Air scrubbing is an end-of-pipe measure to remove ammonia, dust, and other pollutants from the exhaust air of intensive animal housing. There are 3 main types of scrubber which have different strengths and so are often used in combination as two- or three-stage scrubbing systems. Wet acid scrubbers use sulphuric acid to achieve 96% ammonia removal, which likely leads to an overall reduction in nitrous oxide because ammonia is associated with some indirect nitrous oxide emissions. Bioscrubbers (biotrickling filters) typically achieve 70% ammonia removal but the presence of nitrifying bacteria leads to an 80% increase in nitrous oxide emissions, which likely results in an overall increase in GHG emissions. Biofilters use moist organic layers to remove up to 50% of ammonia and also produce additional nitrous oxide (80% increase) due to bacteria, although some authors have reported a reduction in methane so overall the effect is unclear.

Effectiveness		
	Reduced net GHG	
	Wet acid scrubbers	+
	Bioscrubbers	-
	Biofilters	+/-
	Other impacts	
	Ammonia reduction	++
	Odour reduction	++
	Dust reduction	++
	Fertiliser generation	+
Cost		
		£££
Speed of change		
		Moderate
Strength of evidence		
	Quality	3
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

Air scrubbing involves directing air from within the pig unit through one or more filters prior to ventilation to remove ammonia, dust, odour and other pollutant gases. There are three main types of scrubbers: wet acid, biotrickling filter (bioscrubbers) and biofilters (Van der Heyden et al., 2015). Wet acid scrubbers consist of a padded filter that is continually soaked with acid, normally sulphuric (Philippe et al., 2011). The exhaust air blown through the filter and the ammonia dissolves out of the air into the liquid solution as ammonium salts, which can later be used as a liquid fertiliser. Liquid is constantly removed and replaced with fresh water to maintain pH below 5 (Melse, 2009). Bioscrubbers (or biotrickling filters) consist of a padded filter tower that is fixed with a biofilm of nitrifying bacteria. A nutrient solution is continually trickled over the filter to support the bacteria population and to ensure the surface is moist to dissolve pollutant gases (Van der Heyden et al., 2015). The bacteria degrade the dissolved nitrogen compounds into nitrites and nitrates and, as in wet acid scrubbers, solution is removed, and water is added to maintain pH around 7, in order for the bacteria to function. Biofilters consist of a thick layer of moist organic material, such as wood chips, containing microorganisms that oxidise and degrade gaseous compounds (Philippe et al., 2011). Wet acid scrubbers perform best at removing ammonia while bioscrubbers and biofilters are most effective for removing odour, so scrubbers are often combined in two- or three-stage scrubbing systems, often with a water pre-screen to remove dust prior to entry into the system (Montes et al., 2013).

2. How effective is it?

Melse (2009) reports that wet acid scrubbers are 96% effective in removing ammonia and bioscrubbers are 70% effective at removing ammonia. Philippe et al. (2011) suggest ammonia reductions of 65-95% for both types, depending on inlet ammonia concentration, residence time, moisture content, temperature, pH and scrubber material. Van der Hayden et al (2015) extensively reviewed a range of studies and reported average ammonia reductions of 90-95% for wet acid scrubbers, 40-90% reduction for bioscrubbers and 90-95% reduction for multi-stage scrubbers. They found ammonia reductions of 9-50% for biofilters although in some cases emissions were increased. Removal of ammonia has an indirect benefit for nitrous oxide emissions because ammonia is ultimately nitrified into N_2O in the environment (Zhu et al., 2013). However, there is a lack of literature available to quantify this benefit. Where bacteria are present (in biofilters and bioscrubbers) nitrification can take place that produces additional nitrous oxide (Melse, 2009). Van der Heyden et al. (2015) evaluated this in their comprehensive review, reporting an average of 70-80% increase in nitrous oxide emissions from bioscrubbers (one study reported an average of 200% due to longer residence time) and 80-100% increase from biofilters. Wet acid systems had little to no effect on nitrous oxide and no data were available for combined systems. Methane is generally not removed during air scrubbing because of low water solubility, although with long residence times it may be possible to remove through bacterial oxidation in biofilter systems (Melse, 2009). Van der Heyden et al. (2015) report studies achieving 43% methane removal with biofilter systems (up to 65% using non-ionic surfactants), although a residence time of several minutes was required. Further work is needed to confirm the practicality of methane removal (in terms of long residence times) and the net GHG impact, considering increased emission of nitrous oxide from biofilter systems.

3. Where does it work?

Air scrubbing is only possible in indoor pig production with centralised air conditioning, although is applicable to all manure systems and can be installed in new builds or retrofitted. The installation of air scrubbers is BAT and therefore required as part of permitting.

4. How much does it cost?

Air scrubbing incurs significant installation and operating costs in the form of replacement filters, maintenance costs and increased electricity use (Melse, 2009). Costs vary depending on the type of scrubbers required as well as the size of the unit and the amount of volume of airflow required. The BAT reference document suggests that installation of a wet acid scrubbing system would incur investment costs of £26-30 and annual additional operating costs of £7-9 per pig place for a finishing system in the Netherlands, depending on required ammonia reduction (Santonja et al., 2017).

5. How can I do it well?

Air scrubbing systems are likely to be most cost-effective to install in new buildings where the ventilation system and structure of the building can be designed to accommodate the scrubbing system. Generally, multi-stage scrubbers appear to offer the most additional benefits, with higher levels of dust and odour removal than individual scrubbing systems (Van der Heyden et al., 2015). However, consideration of the combined impact on N_2O production is needed to ensure that there are no negative impacts on GHG emissions. One aspect of wet acid scrubbers that needs to be investigated further is the valorisation of the ammonium sulphate that is produced from the absorbed ammonia. Typically, this is used directly as fertiliser, but reports suggest farmers can earn an income of £0.30 income per kg of nitrogen recovered in a 0.1 ammonium sulphate solution, with potential other industry applications.

6. How strong is the evidence?

Multiple reviews have consistently reported ammonia reductions of at least 70% for bioscrubbing systems and over 90% for wet acid and multi-stage scrubbers. There is also broad consensus of benefits on reducing dust and odour. Given that wet acid scrubbers don’t produce additional nitrous oxide, there is likely to be an overall net reduction in GHG through reducing ammonia release and therefore indirect N_2O formation, although more work is needed to quantify this impact. Several reviews have concluded that bioscrubbers produce nitrous oxide (up to 200% more) and it seems unlikely that the reduction in ammonia can counteract this – although again more work is needed to confirm. The same reviews also found that biofilters produce additional nitrous oxide (80-100%), although in some cases biofilters can also mitigate methane emissions. Additional research is needed to systemically evaluate the overall impact on GHG, considering the interactions between ammonia, nitrous oxide and methane in these systems, as well as the practicalities of long residence times.

7. Where can I find further information?

Additional information is available in the best available techniques (BAT) reference document for intensive rearing of poultry or pigs: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/best-available-techniques-bat-reference-document-intensive-rearing-poultry-or-pigs

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1. Comprehensive review of efficacy of air scrubber systems in reducing emissions of GHG, ammonia, odour and particulates from animal housing. Also includes a series of economic evaluations of biofilters for abatement of methane.

2. Descriptive literature review of ammonia emissions from pig houses, including causes and mitigation techniques. Brief overview of air scrubbers in ammonia mitigation, including estimated costs per kg NH_3 removed.

3. Meta-analysis reviewing the effects of various emission abatement techniques, including air scrubbers, in emissions of N_2O, CH_4 and NH_3 from pig houses. Also includes a brief, but thorough descriptive review of the impacts of different types of air scrubbers on each of the three gases.

4. Comprehensive literature review providing a detailed description of the different types of air scrubbers and the impact of each one on ammonia, nitrous oxide, methane, odour and particulate matter. Detailed quantified comparison of the efficacy of several varieties of each type of air scrubber both on its own and in series, with a detailed descriptive summary of the overall effects for each type.

5. Comprehensive literature review of manure management mitigation options for methane and nitrous oxide. Significant, detailed section reviewing the literature surrounding the effects of air scrubbing on methane and nitrous oxide.

10.2.3. Micro-anaerobic digestion

Impact summary

Anaerobic digestion is the breakdown of organic matter by microbes under anaerobic conditions to produce biogas – a mixture of methane, CO_2, and other gases. With minimal purification, biogas can replace natural gas in boilers or CHP units to produce heat and electricity. After digestion, the remaining material (digestate) is an effective fertiliser and can be spread on land in the same way as manure or slurry. AD in Europe has been dominated by large, centralised biogas production sites but there is increasing demand for micro-AD, which can produce enough electricity and heat for a medium-sized farm using slurry, manure, or crop waste. The main benefit of AD is the offsetting of fossil fuel use and grid electricity, with possible additional reductions in GHG emissions from storage and spreading versus untreated manure.

Effectiveness		
	Reduced net GHG	++
	Other impacts	
	Heat generation	++
	Electricity generation	++
Cost		
		££££
Speed of change		
		Slow
Strength of evidence		
	Quality	2
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

Anaerobic digestion (AD) is a natural process in which microorganisms degrade organic material in the absence of oxygen to produce biogas, a mixture of 50-65% methane, 35-40% CO_2 and trace amounts of other gases including hydrogen sulphide, ammonia and hydrogen (Rasi et al., 2007). The biogas can be lightly purified and then used to run a combined heat and power (CHP) unit to generate heat and electricity. After digestion, the remaining material (digestate) maintains much of the nutritional composition of the initial organic material, including a high proportion of ammonium, and can be applied to land as an organic fertiliser (Makádi et al. 2012). Micro-AD (small-scale AD) plants have a CHP electrical output of between 15 to 100kW and can supply the electricity requirements of small to medium sized farming operations (O'Connor et al., 2021). Larger sites can supply surplus electricity to the grid, although there are significant additional investment costs associated with this. There are several different types of micro-AD system which vary in the type of feedstock they can accommodate, their operating temperature, feedstock retention time, biogas yield, degree of automation, number and layout of tanks, storage capacity and several other factors (O'Connor et al., 2021). Where pig slurry is the main feedstock a wet (<15% dry matter), continuous flow micro-AD would generally be most suitable (Farm Advisory Service, 2018).

2. How effective is it?

There are three areas of emissions to consider regarding the effectiveness of micro-AD: energy offset from combustion of biogas, storage of digestate and land application of digestate (including potential offset of inorganic fertiliser). Dennehy et al. (2017) reviewed several studies on all aspects of anaerobic digestion and reported an overall net reduction in GHG emissions from the use of micro-AD of 45-125 kg CO_2e/t manure processed. They found that the main GHG mitigation benefit of micro-AD is through generation of biogas which can be burned via CHP to generate heat and electricity, offsetting fossil fuels and/or grid electricity. GHG emissions from biogas are 0.00021 kg CO_2e/kWh, which is much less than UK grid electricity (0.23314 kg CO_2e/kWh) (UK Gov, 2020). There are embedded emissions in the feedstock used for micro-AD, but where slurry is the main component then this will be relatively low, although more research is needed to investigate this. The reduction in GHG emissions will largely depend on the size of the installation, the type of feedstock used, and the amount of energy use offset. In terms of digestate storage and application, the results are mixed. Dennehy et al. (2017) reported a 50% reduction in GHG emissions from storage of digestate versus equivalent manure storage, as well as unquantified reductions in nitrous oxide during application. Sajeev et al. (2018) found a reduction in methane during storage (29%) but saw increased ammonia (13%) and nitrous oxide (20%) emissions. Overall, they reported a 23% reduction in nitrous oxide, suggesting a net beneficial effect on GHG emissions from storage and spreading. Overall, where there is sufficient utilisation of electricity and heat from biogas combustion, there will likely be a net reduction in overall GHG emissions, although this should be investigated through whole-system, UK-specific case studies.

3. Where does it work?

Micro-AD plants work best where there are large quantities of surplus organic materials, such as crop residues and manure/slurry, and large requirements for on-site heat and electricity. Intensive indoor pig farms are therefore ideal candidates for the technology, particularly farrow-to-finish units as they have large volumes of slurry from the finishing pigs and large heat requirements from the farrowing unit. Micro-AD plants can use straw-based manure or liquid slurry as a feedstock, provided there is regular supply (Farm Advisory Service, 2018).

4. How much does it cost?

There are limited case studies for micro-AD in the UK, with most examples either large scale or on dairy farms. The Farm Advisory Service (2018) suggests a similar biogas yield from both pig and cattle slurry. A case study from Scotland using slurry from 140 dairy cows and additional low-grade silage with a 25 kW CHP cost £210,000 (SRUC, n. d.). A case study from the Netherlands, again using dairy cattle slurry, installed a 65 kW CHP unit to produce 500 MWh of electricity and 1 GWh of heat annually (40-50% of the site electricity requirements). The AD cost £260,000 and the CHP unit cost £130,000, with an estimated ROI of 6-8 years. The economic feasibility of micro-AD will likely depend on the availability of support in the form of grant or loan schemes to help with capital investment and/or feasibility studies.

5. How can I do it well?

There are several companies who specialise in assessing feasibility, designing, installing, and maintaining micro-AD plants. The specific requirements will depend on the production systems, amount of slurry available, space, and logistical considerations, as well as legal, licensing and planning. Anaerobic digestors also require substantial labour resource to manage and maintain. The key to effective implementation is full utilisation of the resulting heat and electricity – O'Connor et al. (2021) quote a recent German study that found that, on average, only 56% of heat generated from AD-CHP plants was utilised. Micro-AD plants can be run using slurry or manure alone, but gas yields can be greatly increased through the addition of other feedstocks such as silage, straw, or beet (Farm Advisory Service, 2018). There is much ongoing research investigating the optimal combination of feedstocks for anaerobic digestion, as well as potential pre-treatment options (Mao et al., 2015).

6. How strong is the evidence?

The main emission reductions from micro-AD is from offsetting grid electricity (and fossil fuels where relevant) through utilisation of heat and electricity from combustion of biogas in CHP. The extent of GHG emission reduction will depend on the size of the installation, the type of feedstock, the amount of biogas generated, and ultimately the amount of electricity and heat offset. There is a lack of contextually relevant data on the GHG emission reductions for a micro-AD installation under a given set of circumstances, which should be addressed going forward. While there are some contradictory findings, the balance of evidence suggests an overall beneficial effect on GHG emission during storing and application of digestate versus raw slurry. There is also potential to reduce emissions via reduced fertiliser use, but this needs to be quantitatively studied.

7. Where can I find further information?

The Farm Advisory Service provide practical information on installing micro-AD on livestock farms: https://www.fas.scot/publication/tn698-anaerobic-digestion-ad-farm-scale/

References

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1. Descriptive review of greenhouse gas abatement measures in animal husbandry with a discussion on emission reductions associated with anaerobic digestion of manure, both from storage and application. The results are not specific to pork production, nor do they quantify the extent of emission reduction.

2. Critical review of greenhouse gas emissions from different pig manure management techniques within the European context. Includes an overview of the main types of digestor and the impact of anaerobic digestion of slurry on overall GHG emission savings due to energy utilisation, reduced synthetic fertiliser use and emissions during storage and application.

3. Meta-analysis reviewing the effects of various emission abatement techniques, including anaerobic digestion, in emissions of N_2O, CH_4 and NH_3 from pig houses. Also includes a brief but thorough descriptive review of the general impacts of anaerobic digestion on each of the three gases.

4. Descriptive literature review which discusses mitigation options for methane and nitrous oxide within livestock production systems, particularly around manure management. Provides a semi-quantitative summary of the overall effectiveness of anaerobic digestion on reducing GHG emissions, including trade-offs between different gases including ammonia.

10.2.4. Hydrogen electrolysis

Impact summary

Hydrogen electrolysis is a method of producing hydrogen gas (H_2) from liquid organic waste (i.e. slurry wastewater). The process works using a microbial electrolysis cell (MEC) which contains electrogenic bacteria. The bacteria break down organic molecules and, with application of external electricity, produce hydrogen gas, methane and CO_2. Hydrogen is a clean-burning, high energy fuel source that may have significant potential future applications. Hydrogen electrolysis is not yet viable on a commercial scale, but may have initial applications as a post-treatment of anaerobic digestion. Further research is needed to optimise the production of hydrogen and to scale the technology.

Effectiveness		
	Reduced net GHG	+
	Other impacts	
	Hydrogen production	+
	Improved AD efficiency	+
	Remove pollutants	+
Cost		
		£££+
Speed of change		
		Slow
Strength of evidence		
	Quality	3
	Context	1
	Overall	1

Narrative Summary

1. What is the practice?

Hydrogen has the potential to be a sustainable energy source in the future because it has a high energy value and the only by-product of combustion is water. Hydrogen electrolysis is the production of hydrogen gas (H_2), which until now has been done using water in an energy-intensive process (Kadier et al., 2014). Microbial electrolysis cells (MECs) present a novel method of producing hydrogen from organic waste streams, which has much lower energy requirements than traditional water-based approaches (Zhang & Angelidaki, 2014). There are several different types of microbial electrolysis cell, but a typical two-chambered MEC consists of two chambers separated by a selectively permeable membrane. One chamber contains the organic substrate (which could be the liquid fraction of pig slurry or AD digestate) and an anode coated in electrogenic bacteria. The other chamber contains a cathode in a reactor solution. When the bacteria break down (oxidise) the organic material in the liquid, they produce electrons, protons and CO_2. The protons migrate across the membrane while the electrons are pushed through a circuit via a small external power supply. At the cathode these protons and electrons combine to form hydrogen gas, while at the anode leftover protons combine with CO_2 to form methane and water (Hua et al, 2019). The proportion of methane and hydrogen varies (from 86% methane to 77% hydrogen) depending on the reaction parameters including the bacteria present, substrate, temperature, pH, and reactor solution (Kadier et al., 2014). These parameters are adjusted based on the desired output.

2. How effective is it?

Given that hydrogen electrolysis is not being done in commercial contexts it is difficult to determine its impact on GHG emissions. The greatest potential benefits are likely to be in offsetting the use of fossil fuels although hydrogen powered vehicles and machinery so emissions will be influenced by the difference in GWP between hydrogen fuel and diesel/petrol. Hydrogen electrolysis also relies on solid/liquid separation which has lower GHG emissions overall (storage and application) but higher emissions during storage than unseparated slurry or manure (Dennehy et al., 2017). The process of hydrogen electrolysis requires external electricity, although the amount required various between experiments. Lourinho & Brito (2021) discuss three experiments with large variation in external electricity consumption: 4.77 kWh/kg ammonia removed, 16.6 kWh/kg ammonia removed and 152kWh for 90% ammonia removal in 1m^3 manure. More research is needed to determine exactly how much external electricity is required in the context of hydrogen production, and whether or not that electricity can be supplied from renewable sources, such as the biogas produced during AD.

3. Where does it work?

Wagner et al. (2009) were the first to demonstrate viability of hydrogen electrolysis from pig wastewater using a MEC at laboratory scale. They achieved ~1m^3 H_2 per m^3 wastewater per day, with a ~70% reduction in organic pollutants. The electrical energy value of that hydrogen was ~190% of the electricity used to produce it. Within the academic literature there are no examples of hydrogen electrolysis being performed at farm scale using pig slurry.

4. How much does it cost?

As hydrogen electrolysis isn't being deployed at scale it is difficult to determine potential costs. However, given that it will likely accompany AD (or solid/liquid separation system) there are already significant prerequisite investment costs. The MEC itself is likely to incur substantial additional investment and operating costs, although several authors suggest that it will be economically viable, particularly if much of the required electricity is produced from biogas (Hua et al., 2018).

5. How can I do it well?

There is still a lot of uncertainty in how hydrogen production can be optimally achieved at commercial scale. There is a lot of research being done at laboratory level to determine the best anode and cathode materials, membrane materials, pre-treatments for the wastewater and microbial populations. There are then additional challenges around scalability of the system, long-term operational stability, availability of capital investment, economic feasibility and environmental impact (including a GHG perspective). It seems likely that hydrogen electrolysis will be best suited as a complement to existing anaerobic digestion, with the electricity produced from CHP providing the energy needed for hydrogen production from the remaining organic residues in the liquid fraction of the digestate. This would produce a virtually 100% pollutant free liquid and partially close the waste loop from intensive pig production – especially important where there are strict limits on land spreading (Lourinho & Brito, 2021).

6. How strong is the evidence?

Hydrogen electrolysis is a promising future technology with encouraging results from laboratory experiments. There are several information gaps around how to maximise hydrogen production at laboratory scale and then how to implement at commercial scale. It is too early to determine the potential GHG mitigation impact of hydrogen electrolysis of pig waste.

7. Where can I find further information?

AHDB have some information on hydrogen electrolysis, which will be updated as the technology develops and case studies become available: https://ahdb.org.uk/knowledge-library/hydrogen-electrolysis

References

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1. Comprehensive literature review covering all aspects of electrolytic treatment of pig wastewater. Discusses different electrode materials, system layouts, and operating parameters, with evaluation of MEC-AD in a commercial setting and insight into the potential for hydrogen production.

2. Review of microbial electrolysis cells and their applications including removal of pollutants and generation of methane and hydrogen from wastewater. Includes overview of combined technologies such as MEC-AD, MEC-MFC and others.

3. Literature review of the major substrates which have been evaluated for production of hydrogen through microbial electrolysis cells. Includes a section on pig wastewater, with recent experimental data and a review of remaining challenges.

4. Comprehensive literature review of microbial electrolysis cells, including possible applications and future challenges.

5. Experimental evaluation of hydrogen yield from electrolysis of pig wastewater in a single-chamber MEC reactor.

10.2.5. Precision feeding

Impact summary

Precision livestock feeding aims to precisely match animal nutrient supply to nutritional requirements, based on collected data such as age, weight and performance. In practice, this ranges from manually supplementing feeding to sows based on litter size, to automatic feeding systems that monitor the feed intake and average weight of a group of finishing pigs, precisely adjusting the feed ration on a daily basis to minimise excess nutrition. Precision feeding allows each animal to achieve optimal production for the minimum amount of feed, which has impacts on production costs and, given that feed accounts for 70% of the GHG emissions in pork production, GHG emissions as well.

Effectiveness	
Reduced net GHG	++
Other impacts	
Reduced costs	++
Improved welfare	+
Cost	
	£-£££
Speed of change	
	Fast - moderate
Strength of evidence	
Quality	3
Context	2
Overall	2

Narrative Summary

1. What is the practice?

Precision feeding is a method of matching animal nutrition more closely to actual nutritional requirements, and includes: evaluation of feed nutritional profile, precise determination of nutrient requirements, formulation of diets that limit excess nutrients and the continual adjustment of the diet to meet the ever-changing nutritional needs (Pomar et al., 2009). In practice, this means continually adjusting the diet (i.e. daily) for a group of similar animals or for individuals. Individual precision feeding is already widely practiced in breeding sows and the dairy cow herd, where feed is adjusted based on performance, often using radiofrequency identification (RFID) ear tags. Finishing pigs, however, are typically given 2-4 different diets over their grow-finish phase of production, which leads to excess use of feed and nutrients than are required for growth (Niemi et al., 2010). Group precision feeding uses varying degrees of technology to allow the diet to be adjusted on a daily basis in order to increase feed efficiency and therefore reduce GHG emissions (Pomar & Remus, 2019). Precision feeding is regarded as a form of precision livestock farming (PLF), which aims to improve the efficiency of livestock production through monitoring, modelling, and managing aspects of animal production (Tullo et al., 2019). It is also an example of autonomous maintenance, which is one of the pillars of total productive maintenance (TPM) – a lean management concept that aims to achieve incremental improvements across a production system by implementing maintenance as part of normal routines.

2. How effective is it?

Several authors have reported reduced nitrogen and phosphorous intake and excretion in both individual and group precision feeding regimes, as well as reduced overall feed use (Pomer & Remus, 2019). Niemi et al. (2010) used modelling techniques to demonstrate savings of 2–3 kg barley and 1 kg soybean meal per pig during the finishing period under precision group feeding versus two-phase feeding. Andretta et al. (2018) provide the only study that specifically investigated the impact of precision feeding on GHG emissions, reporting a 6% reduction in life cycle GHG emissions after implementation of individual precision feeding.

3. Where does it work?

Precision feeding is a potentially broad term for any system to match animal feed provisions more closely with feed requirements. It can be applied to farrowing sows in the form of altered diets based on reproductive performance, body weight or body condition, either using automatic feeders or manual adjustments. For growing and finishing pigs, precision feeding normally consists of two feed blends – one high energy and one low energy – that are blended in slightly different proportions each day to track the changes dietary needs of the pigs as they grow (Pomar & Remus, 2009). This would typically be distributed using automated feeders that take into account the age of the group, the average feed intake (calculated by the feeder) and the average weight (calculated by scales positioned in front of the feeder). These systems can be implemented in any finishing system, either straw or slat based.

4. How much does it cost?

The cost of a precision feeding system depends on the level of automation. A small amount of additional feeding, manually supplied to underperforming sows is relatively cheap, while a fully automated feeding system with weighing for finishing pigs will be relatively expensive. However, these systems have the potential to reduce production costs by 8% (Pomar & Remus, 2019).

5. How can I do it well?

In practice, precision feeding involves collecting data on individual animals or groups. For sows this would include age, parity, litter size and body condition, while for finishing pigs it could include age, weight and growth rate. This data is then modelled to determine the optimal feed amount and composition. Initial precision feeding models have used lysine as the limiting amino acid in pig growth, with other amino acids and nutrients proportional to it (Pomar et al., 2009). The model determines the optimal daily nutritional profile of the feed based on an average pig (or the pig with the 80th percentile growth rate). Finally, the optimal feed must be delivered to the pigs. This is normally done by preparing two feed blends – one being the maximum nutrient requirements of the most demanding pig at the start of the growth phase, and the other being the minimum nutrient requirements of the least demanding pig at the end of the finishing phase. The use of feeders that monitor feed intake (either individually or a group average) and scales to monitor individual or group average weight will increase the accuracy of the model.

6. How strong is the evidence?

There is a broad and robust evidence base in support of reduced nitrogen excretion due to precision feeding (Pomar & Remus, 2019). However, only one study specifically looked at the overall effect on GHG emissions. Given that feed accounts for 70% of GHG emissions, any reduction in feed use will reduce the GHG emissions of pig production. Further research is needed from a whole system approach on the GHG emission impacts of precision feeding.

7. Where can I find further information?

Precision feeding is an example of autonomous maintenance, which is one of the pillars of total productive maintenance – a method of embedding standard procedures into daily routines to improve consistency and efficiency. Information on total productive maintenance can be found on the AHDB website: https://ahdb.org.uk/from-gilt-watch-to-smartpork

References

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4. Niemi, J. K., Sevón-Aimonen, M. L., Pietola, K. & Stalder, K. J. (2010) The value of precision feeding technologies for grow–finish swine. *Livestock Science* **129**(1-3): 13-23.

5. Andretta, I., Hauschild, L., Kipper, M., Pires, P. G. S. & Pomar, C. (2018) Environmental impacts of precision feeding programs applied in pig production. *animal* **12**(9): 1990-1998.

1. Literature review of precision feeding in pig production with details of implementation and future challenges. Includes figures for cost-savings, nitrogen and phosphorous excretion, and greenhouse gas emission reductions.

2. Descriptive review of precision feeding in growing-finishing pigs with evidence from Brazil. Provides figures for reduction in feed costs and N and P excretion.

3. Comprehensive literature review discussing all aspects of precision livestock farming with a section on precision feeding in pigs. References data on reduction of nitrogen and phosphorous excretion.

4. Study to determine the economic impact of implementing a daily-optimised group feeding regime vs. a conventional two-phase feeding regime.

5. Study to evaluate the environmental impact of switching from a conventional feeding system to precision feeding in Brazilian farrow-to-finish pig production. Uses LCA to determine GHG emissions from conventional, group precision feeding, and individual precision feeding.

10.3. Potatoes

10.3.1. Seal buildings to prevent air leaks

Impact summary

Air leaks in potato stores can necessitate increased energy use for refrigeration and/or ventilation to maintain correct environmental temperature for the stored crop. By reducing structural air leaks, energy requirements can be reduced, reducing costs as well as the associated GHG emissions from the production of that energy.

Effectiveness		
	Reduced net GHG	++
	Other impacts	
	Improvements in marketable yield	+/-
Cost		
		£-£££
Speed of change		
		Fast-Moderate
Strength of evidence		
	Quality	2
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

Potato stores are most efficient at maintaining crop quality and minimising energy consumption when the temperature and humidity can be controlled within a narrow window. Internal store conditions are usually different from the ambient temperature outside of the potato store, which necessitates the use of refrigeration and/or ventilation. Ingress of warm air into the potato store through air leaks increases the temperature, which requires more energy to be used by the refrigeration and/or ventilation systems to maintain the target temperature. By sealing air leaks, energy need will be reduced, reducing cost and with associated reduction in the GHG emissions from the store.

There are different ways in which air leaks can occur. It may be that for some stores, air leaks were always present, particularly where the potato store was not purpose-built and instead was converted from an existing building. Air leaks could also develop through damage (e.g. broken panels, and machinery damage around doorways) or deterioration (e.g. perishing of rubber seals around doors). Older equipment and buildings, and a lack of servicing increase the risk of air leaks.

NOTE: This practice is connected to optimising insulation (the REA that follows this), as both are practices that seek to reduce the ingress of heat into the store during warm weather conditions. Often, the addition or replacement of insulation also seals air leaks, which suggests that these two practices should be considered together.

2. How effective is it?

The impact of the changes will depend on the initial specific conditions of the potato store. Older stores, particularly those converted from general purpose farm buildings, are likely to have greater risk of air leaks. Modern, purpose-built stores will have been constructed to higher standards with less risk of air leaks. Where there are significant air leaks, this can be one of the most effective practices for reducing the energy requirements of a potato store.

Evidence: In data collected by Sutton Bridge CSR and the Farm Energy Centre, a third of the 40 assessed potato stores fell below the acceptable standard of air tightness, whilst only a limited number were rated as good (Scrivener, 2015). It was also found that air leakage can be responsible for up to 37% in pre-pack stores, and 55% in processing potato store’s total energy consumption.

Evidence: Computer simulations of a potato store suggest sealing air leaks in potato stores with very poor air tightness could lower energy requirements by approximately 33% and 50% for pre-pack and processing potatoes, respectively (Swain et al., 2013). However, when assessing actual stores, the energy losses from air leakage tended to be much smaller (e.g. <5%).

The extent to which a reduction in energy would impact on the GHG emissions of potato storage will depend on the source of energy used. If the electricity supply is from renewable sources, the opportunity to reduce GHG emissions is more limited than where energy is provides from grid electricity.

3. Where does it work?

The need for the practice and its potential impact will depend on the initial specific conditions of the potato store. Self-checks as well as professional checks for determining the need for sealing air leaks are described below.

4. How much does it cost?

Due to the uniqueness of each store, the requirements will be bespoke and therefore it is not possible to calculate an average cost. Where there are only limited air leaks (e.g. due to damaged seals around doors), sealing the building is relatively low cost. Costs can be higher if repairs need to be made to the fabric of the building. However, the costs of sealing those air leaks could generally reduce costs from lower energy requirements. Another factor to consider is that through reducing air leaks, it will be easier to maintain optimal storage conditions for achieving the best quality of potato. For example, leakage of warm air into a potato store can result in the formation of condensation, which if allowed to drip onto the potatoes, can result in damage to the crop.

Evidence: One case study of upgrades to a potato store found that air leakage of 34% an hour was reduced to <5% an hour through the use of spray foam insulation and an air divider curtain, which resulted in a 42% electricity saving. The work cost £20,300, but the reduction in electricity used gave a return on investment within 5 years (AHDB, 2019c).

5. How can I do it well?

Very simple checks can be made by feeling for draughts on windy days or by checking how lightproof the store is on a bright day with the store closed. A more thorough approach to identifying air leaks is using an air permeability pressure test (e.g. AP50, which is the measure of air leakage from a building every hour at a reference pressure of 50 Pa). A method has been developed specifically for potato stores to provide assessment of the whole building. This quantifies how tightly the store is sealed, which allows comparison with benchmarks. New buildings aim for an air leak value of less than ≤ 3 $m^3/h.m^2$. Another assessment approach identifies air leaks using a thermal imaging camera to show warm patches from the ingress of warm air. Sutton Bridge CSR recommend seeking expert advice to assess the store and identify the best options for sealing (Cunnington, 2019).

Common areas for air leaks are the junction between doors and the building (both main and personnel doors), ventilation louvres and louvre frames, and joints in the building (e.g. filling joints on roof eaves). These air leaks can be the result of poor fitting, damaged or perished seals or damage to the building's fabric, both mechanical and rodent.

Sealing air leaks:

- Replace missing, damaged and perished seals
- Adjust doors to make a tight seal when closed
- Service louvres and vents to make sure these form a close seal when shut
- Seal building joints. (Also likely be addressed as part of the replacement of insulation)

Note that the target of this practice is to seal the building against all structural air leaks. Some movement of air between the store and outside is required to prevent the build-up of CO_2 resulting from potato respiration; however, this should be through a controlled process using fans and vents.

6. How strong is the evidence?

There is little within academic research publications on this. Based on the Evidence for Farming Initiative Draft Evidence standards, this would be classed as a '2' due to the lack of published studies. However, the recommendations presented here are based on information provided by AHDB via The Potato Store Manager's Guide, which is the result of robust data and extensive experience in both research and commercial stores.

7. Where can I find further information?

AHDB provide advice and auditing of potato storage. This includes StoreCheck, which is a service for assessing the performance of the store and identifying where improvements can be made.

https://ahdb.org.uk/storecheck

https://ahdb.org.uk/about-sutton-bridge-csr

References

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3. **Cunnington, A. (2019)** Potato store managers' guide. Third edition, minor edits. AHDB.
4. **Cunnington, A. (2020)** This one tip could make your potato store more efficient and give better sprout control. Available at: <https://ahdb.org.uk/news/this-one-tip-could-make-your-potato-store-more-efficient-and-give-better-sprout-control> [Accessed 23rd February 2021]
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7. **Swain, J., Coe, O., Cunnington, A. and Saunders, S. (2013)** Reducing the Energy Cost of Potato Storage. Final report. Ref: R439. Report prepared for The Potato Council.

1. Case study on improvements to a potato store that had significant air leakage. Investment costs for the upgrades are presented alongside the energy and cost savings that result.

2. Pamphlet providing information on the opportunities for improving the energy efficiency of potato storage.

3. Guide to the management of potato stores. Considers this from the perspective of maintaining potato quality as well as minimising energy use. This information is based on significant experience and experimental work.

4. Website article describing the main opportunities for improving potato store efficiency. Based on the same body of data that will have fed into Cunnington (2019).

5. Article in farming press on managing potato stores for energy efficiency. Includes reference to unpublished results from a series of potato store energy audits conducted by Sutton Bridge CSR and the Farm Energy Centre. Further reference to this data was not found in the grey literature search.

6. Experimental evaluation of the energy efficiency of potato stores, utilising both measurements of potato stores and computer simulations of changes to their structure and configuration.

7. Experimental evaluation of the energy efficiency of potato stores, utilising both measurements of potato stores and computer simulations of changes to their structure and configuration.

10.3.2. Optimise insulation

Impact summary

Poor insulation in potato stores will increase energy use for refrigeration and/or ventilation to maintain correct temperatures for stored product. By upgrading or repairing insulation, energy requirements can be reduced, reducing costs as well as the associated GHG emissions from the production of that energy.

Effectiveness		
	Reduced net GHG	++
	Other impacts	
	Improvements in marketable yield	+/-
Cost		
		£-£££
Speed of change		
		Fast-Moderate
Strength of evidence		
	Quality	2
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

Potato stores are most efficient when the temperature and humidity can be controlled within a narrow window, often at lower temperatures than the external ambient air. Potato stores use insulation to reduce the ingress of heat energy into the store. The more heat energy entering the store, the greater the energy required for refrigeration and/or ventilation to keep the temperature at the correct level.

The quality of insulation will depend on the type of material, its thickness, how well fitted it is and whether it is free of damage. By providing optimal insulation, the energy requirements and, therefore, GHG emissions from electricity use will be minimised.

Optimising insulation is closely related to air leakage (the REA that precedes this), as both are practices that seek to reduce the ingress of heat into the store during warm weather. Often, the addition or replacement of insulation also seals air leaks, and these two practices should be considered together.

2. How effective is it?

The impact of the changes to insulation will depend on the specific initial conditions of the potato store. Older stores, particularly those converted from general purpose farm buildings, are likely to have thinner insulation (in some cases less than 50 mm). Modern, purpose-built stores will have been constructed to higher standards with thicker insulation up to 120 mm. Where insulation is inadequate, upgrading this to thicker insulation is one of the most effective practices for reducing the energy requirements of a potato store. There is lack of published data specifically showing the impacts of upgrading insulation will have on GHG emissions. There is a suggestion that, where insulation is currently inadequate, upgrading insultation can reduce GHG emissions by more than 50% (Carbon Trust, 2010). In contrast, a computer simulation found an energy saving of 11.8% was found from upgrading existing 50 mm insulation with an additional 50 mm of spray-on insulation (Swain et al., 2013); although GHG emissions were not modelled, it is likely that the 11.8% energy saving would have only resulted in a commensurate reduction in GHG emissions.

The extent to which a reduction in energy would impact on the GHG emissions of potato storage will depend on the source of energy used. If the electricity supply is from renewable sources, the opportunity to reduce GHG emissions is more limited than from traditional sources.

3. Where does it work?

Greater energy, and therefore GHG emission savings, are achievable where existing insulation is of inadequate thickness or damaged. The length of time of storage and the storage temperature will also influence how beneficial the practice would be, with stores that are used for long term storage into the warmer spring and summer months seeing greater benefits than those used for short term storage into the cooler autumn and winter months.

4. How much does it cost?

Due to the uniqueness of each store, the requirements will be bespoke and therefore it is not possible to calculate an average cost. Costs may be minimal if the work only requires replacement of small areas of damaged insulation. Where all insulation requires replacement, this may necessitate higher costs.

Evidence: In a case study conducted by the Carbon Trust (2010), the insulation of a 1,000-tonne refrigerated potato store was supplemented with an additional 50 mm of spray-on foam polyurethane. The total cost of the upgrade was £17,000, which led to annual savings of £6,400 giving a return on investment of approximately 3 years.

A factor to consider is that through improving insulation, it will be easier to maintain optimal storage conditions for achieving the best quality of potato. It will also limit the formation of condensation, which can also result in potato damage and a loss of quality. This has the potential to improve marketable yield and value of potatoes that leave the store.

5. How can I do it well?

It is recommended that a minimum thickness for roof insulation of 75 mm and 50 mm for the walls of refrigerated and ambient stores, respectively (Cunnington, 2019); however, optimum insulation thickness will vary with the material used (Carbon Trust, 2010). Identify current insulation thickness, such as through inserting a narrow diameter probe into the insulation, and compare to recommendations. Check for damage to the insulation and identify thermal bridges such as building steel stanchions, or concrete through the insulation. It is recommended to get expert assessment of the state of the insulation. This could take the form of thermal imaging using specialist equipment to identify temperature hotspots where insulation is inadequate.

There are various insulation products available, including spray-on foam or extruded board polyurethane. Upgrading insulation can also help to address air leaks; spray-on foam in particular is very effective (Carbon Trust, 2010). The insulation can be supplemented with products such as low emissivity paints and reflective films, which reduce the solar gain.

The thickness and state of the insulation may vary around the potato store, which may mean that only part of the potato store needs the insulation addressed. For example, if existing insulation is already of the required thickness, but some insulation panels are damaged, it would make financial sense to only replace the damaged panels.

At the high relative humidity of potato stores, condensation can form on the potato store structure if its temperature is below that of the air within the store. If this condensation is allowed to drip onto potatoes, it can lead to disease and a loss of potato quality. Having adequate insulation reduces the risk of internal surfaces cooling and condensation forming.

6. How strong is the evidence?

There is little within academic research publications on this. Based on the Evidence for Farming Initiative Draft Evidence standards, this would be classed as a ‘2’ due to the lack of published studies. However, the recommendations presented here are based on information provided by AHDB via The Potato Store Manager’s Guide, which is the result of robust data and extensive experience in both research and commercial stores.

7. Where can I find further information?

AHDB provide advice and auditing of potato storage. This includes StoreCheck, which is a service for assessing the performance of the store and identifying where improvements can be made.

https://ahdb.org.uk/storecheck

https://ahdb.org.uk/about-sutton-bridge-csr

References

1. **Carbon Trust (n.d.)** Potato farming fact sheet: Detailed advice for potato growers.
2. **Carbon Trust (2010)** Interest-free investment in crop store insulation cuts costs and increases income. Agricultural case study CTS184.
3. **Cunnington, A. (2019)** Potato store managers' guide. Third edition, minor edits. AHDB.
4. **Cunnington, A. (2020)** This one tip could make your potato store more efficient and give better sprout control. Available at: <https://ahdb.org.uk/news/this-one-tip-could-make-your-potato-store-more-efficient-and-give-better-sprout-control> [Accessed 23rd February 2021]
5. **Swain, J., Coe, O., Cunnington, A. and Saunders, S. (2010)** Reducing the Energy Cost of Potato Storage. Final report. Ref: R439. Report No. 2013/8. Report prepared for The Potato Council.
6. **Swain, J., Coe, O., Cunnington, A. and Saunders, S. (2013)** Reducing the Energy Cost of Potato Storage. Final report. Ref: R439. Report prepared for The Potato Council.

1. Pamphlet providing information on the opportunities for improving the energy efficiency of potato storage.

2. Case study of improvements to insulation in a potato store. Costs and energy savings are presented. Limited information on the initial conditions of the potato store and no given GHG emission reduction figures.

3. Guide to the management of potato stores. Considers this from the perspective of maintaining potato quality as well as minimising energy use. This information is based on significant experience and experimental work.

4. Website article describing the main opportunities for improving potato store efficiency. Based on the same body of data that will have fed into Cunnington (2019).

5. Experimental evaluation of the energy efficiency of potato stores, utilising both measurements of potato stores and computer simulations of changes to their structure and configuration.

6. Experimental evaluation of the energy efficiency of potato stores, utilising both measurements of potato stores and computer simulations of changes to their structure and configuration.

10.4. Protected Horticulture

10.4.1. Use of biogas for heating

Impact summary

In heated glasshouse operations, the combustion of fossil fuels for heating is by far the largest contributor to GHG emissions, typically accounting for 90-95% of emissions. Biogas, which is predominantly comprised of methane, is produced during the anaerobic breakdown of organic matter and after light processing can be used in place of natural gas in boilers and CHP units. Biogas can be produced via anaerobic digestion (AD) or via landfill and has much lower GHG emissions than natural gas. AD has historically been in the form of large-scale, centralised plants although farm-scale micro-AD is becoming increasingly feasible. By offsetting the use of grid electricity and fossil fuels such as natural gas and heating oil, biogas has the potential to greatly reduce GHG emissions while still allowing crop CO_2 enrichment.

Effectiveness		
	Reduced net GHG	++
	Other impacts	
	Heat generation	++
	Electricity generation	++
	CO_2 enrichment	++
Cost		
		£££+
Speed of change		
		Slow
Strength of evidence		
	Quality	3
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

This practice involves replacing conventional fuels, such as natural gas and heating oil, with biogas. Biogas is comprised mostly of methane and is produced through anaerobic breakdown of organic material. It can directly substitute natural gas in combined heat and power (CHP) units and, in addition, produces fewer nitrogen oxides during combustion (Gruda et al., 2019). Burning of biogas produces CO_2 that is suitable for crop enrichment, although some purification is needed to remove water, hydrogen sulphide and other compounds. There are three main sources of biogas: landfill sites, centralised anaerobic digestors, and on-site anaerobic digestors. In the UK horticulture sector, on-site AD is currently the most promising model because centralised AD typically burns biogas for electricity and landfill biogas has higher pollutant levels and is more difficult to purify (Dion et al., 2011). On-site AD can utilise crop residues to produce a consistent biogas as well as digestate fertiliser, although has additional considerations including labour and investment costs, planning, and continuity of feedstock.

2. How effective is it?

In heated glasshouse operations, CO_2 released from burning natural gas and heating oil is by far the largest contributor to GHG emissions, typically accounting for 90-95% of the total emissions (Hospido et al., 2009). Biogas has GHG emissions of 0.00021 kg CO_2e/kWh, which is much lower than natural gas (0.18387 kgCO_2e/kWh) and LPG heating oil (0.21448 kgCO_2e/kWh) (UK Gov, 2020). Therefore, use of biogas as a replacement for fossil fuels reduces net GHG emissions. Where crops are grown specifically to maintain anaerobic digestors, there are additional embedded emissions which will reduce the GHG benefit, although the consistency of material and guaranteed supply can improve biogas output.

3. Where does it work?

Biogas has large potential to reduce GHG emissions in large horticulture operations with extensive heated glasshouse infrastructure. On-site anaerobic digestion is likely to be most feasible for large growers with packaging/processing units that generate consistent waste organic material all year round. This ensures consistent feedstock needed to keep the AD running optimally, while also avoids the use of primary products which have embedded GHG emissions and land use changes. It is also important to consider the alternative uses for the organic material that is used in these systems, e.g. composting or soil amelioration, although the digestate from the process does provide a nutrient rich organic material. There may be avenues to purchase biogas directly from other anaerobic digestion plants, however biogas is not yet price competitive with natural gas.

4. How much does it cost?

The cost of producing biomethane (purified biogas that is suitable for use in grid electricity generation) is around £50-105 MWh, although biogas for protected horticulture has lower purification requirements than grid electricity. Natural gas costs around £40 MWh although the price is volatile (Business Energy, n. d.). If the site is very large scale, it is also worth considering selling surplus electricity to the grid to improve cost-effectiveness. Where on-site AD is used, the investment and operating costs are substantial, although there are few case studies in horticulture to be able to quantify figures for a typical installation size and type.

5. How can I do it well?

There are several technical considerations around biogas itself and its production via AD. Biogas is typically burned in a CHP boiler to produce heat, electricity and CO_2. One challenge is that plant CO_2 requirements are often out of sync with heat requirements (Li et al., 2018). One method to address this by using heat capture and storage, for example in a water tank. Biogas can be combusted to heat the water tank, generating CO_2 for crop enrichment, and then the heat can be transferred from the stored tank in the evening when the temperature begins to drop. Purification of the CO_2 also needs to be considered, with several options for gas cleaning. Where anaerobic digestors are used, then it is important to factor in the additional time/labour requirements for managing and maintaining the AD, and ensuring the feedstock is consistent in order to stabilise gas yield.

6. How strong is the evidence?

Where natural gas or other fossil fuels are replaced with biogas, there will be reduction in GHG emissions. They extent of the reduction depends on the source of biogas and the amount of heat/electricity offset. There are still barriers to be overcome, including development of a biogas supply chain at a price-point that is competitive with natural gas, and around the issue of unsynchronous crop requirements for heat and CO_2. It is difficult to confidently determine the overall GHG impact without case studies in the protected horticultural sector.

7. Where can I find further information?

There were no relevant farmer-focused publications available for biogas or anaerobic digestion in the protected horticulture sector.

References

1. Gruda, N., Bisbis, M. & Tanny, J. (2019) Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production–A review. *Journal of Cleaner Production* **225**: 324-339.

2. Dion, L. M., Lefsrud, M. & Orsat, V. (2011) Review of CO2 recovery methods from the exhaust gas of biomass heating systems for safe enrichment in greenhouses. *Biomass and Bioenergy* **35**(8): 3422-3432.

3. Li, Y., Ding, Y., Li, D. & Miao, Z. (2018) Automatic carbon dioxide enrichment strategies in the greenhouse: A review. *Biosystems Engineering* **171**: 101-119.

4. Jaffrin, A., Bentounes, N., Joan, A. M. & Makhlouf, S. (2003) Landfill biogas for heating greenhouses and providing carbon dioxide supplement for plant growth. *Biosystems Engineering* **86**(1): 113-123.

1. Comprehensive literature review of the main impacts of protected horticulture on GHG emissions and practices for mitigation. Short section summarising key literature on the use of biogas in protected horticulture, although no quantification of impacts.

2. Descriptive review of CO_2 recovery from biogas and biomass heating systems for use in protected horticulture. Discusses the feasibility of landfill biogas in commercial horticulture including the purification process.

3. Comprehensive literature review of CO_2 enrichment methods in protected horticulture. Includes semi-quantitative comparison of landfill and AD biogas, and multiple types of biomass fuel vs. fossil fuel sources in terms of emissions and purification requirements.

4. Feasibility study on the use of landfill biogas in demonstration and commercial glasshouses in France. Examines hydroponic rose crops in 300 m^2 plastic greenhouses over 24 months.

10.4.2. Use of biomass for heating

Impact summary

Biomass fuels generally have very low levels of GHG emissions compared to fossil fuels (e.g. natural gas, 0.18387 kgCO_2e/kWh or LPG, 0.21448 kgCO_2e/kWh) (UK Gov, 2020). Biomass boilers typically use wood pellets (0.01545 kgCO_2e/kWh), which are made from compressed sawdust (a by-product of the wood industry). In the UK the main alternative biomass sources are cereal or miscanthus straw (0.01629 kgCO_2e/kWh) or wood chips / logs from short rotation coppice or short rotation forestry (0.01545 kgCO_2e/kWh). The CO_2 produced during combustion of biomass crops are part of the biotic carbon cycle – the CO_2 was captured during photosynthesis and then re-released during combustion with no net change in atmospheric CO_2 concentrations. Therefore, the only net emissions are those embedded in the growing, harvesting, transport and processing of the raw material. The source of the biomass has a role to play in further reducing emissions, aiming to utilise waste products rather than crops specifically grown for biomass, and reducing the risk of unintended consequences, e.g. changes in land use elsewhere.

Effectiveness		
	Reduced net GHG	++
	Other impacts	
	Heat generation	++
	Electricity generation	++
	CO_2 enrichment	+
	Cost savings	+
Cost		
		£££
Speed of change		
		Slow
Strength of evidence		
	Quality	4
	Context	3
	Overall	3

Narrative Summary

1. What is the practice?

A biomass heating system involves the combustion of biomass to produce energy and CO_2. Biomass fuel is typically wood pellets, which are made from compressed sawdust (a by-product of the wood industry), straw and miscanthus can also be used (Gruda et al., 2019). The fuel is then burned in a boiler to produce heat (and electricity if CHP) and CO_2. Compared to biogas, the resultant flue gas has higher levels of ash and other pollutants so use in CO_2 enrichment is more challenging, although recent advances in scrubbing technology now make it feasible (Dion et al., 2011).

2. How effective is it?

All sources of biogas have low GHG emissions compared to natural gas. Wood pellets are a common biomass fuel and have an emission factor of 0.01545 kgCO_2e/kWh, while natural gas has an emission factor of 0.18387 kgCO_2e/kWh (UK Gov, 2020). The emissions produced during combustion of biomass material is subsequently recaptured by photosynthesis into new biomass as part of biogenic carbon cycles. Therefore, the main sources of emissions from biomass products are the embedded emissions from fuel used to plant, manage, harvest and transport.

3. Where does it work?

Biomass heating is only applicable to heated glasshouses. The more heating that is required (and therefore the more natural gas that can be offset) the greater the likely GHG emission benefit. Given the required investment and operating costs, this practice will be most applicable to large-scale growers who can achieve economies of scale.

4. How much does it cost?

FEC Energy (2016) provide two case studies of ornamental growers using biomass CHP in Ireland. The first grower had 5 ha of glasshouse over two sites and replaced two 4MW oil boilers with two 990kW woodchip boilers. The capital cost was £1.3m, although they received grant funding and reduced fuel costs from £430,000 to £315,000. The second case study consisted of a single 1.2 ha glasshouse site which replaced two 950kW gas oil burners with a single 995MW wood pellet boiler. The capital investment was £284,000, with fuel costs reduced from £186,000 to £139,000.

5. How can I do it well?

As with all heating techniques, there is potential to use thermal energy storage to capture excess heat energy and release it when needed. This is particularly important due to the mismatch between heat requirements (at night) and CO_2 requirements (during the day) (Li et al., 2018). The main things to consider when planning biomass energy generation are the size and type of boiler, and the feedstock used. AHDB (2016) provide an overview of different boiler types with indicative costs.

6. How strong is the evidence?

Biomass boilers have been installed in several large commercial glasshouses in the UK, which suggests economic viability. In terms of GHG reduction, there is limited evidence on a practical level, and is likely variable based on the type of system, the fuel source used and the fuel source being replaced; however, where biomass is used to offset natural gas, there will be a large GHG benefit. Knowledge sharing within the industry would go a long way to clarify the GHG and economic benefits, as well as provide useful information on best installation practices.

7. Where can I find further information?

AHDB provide an overview of different boiler options, including pros and cons:
https://projectblue.blob.core.windows.net/media/Default/Horticulture/GrowSave/31%20-%20Biomass%20CHP.pdf

FEC Energy discuss different biomass fuels and provide some case studies of biomass being applied to the protected horticulture sector in Ireland:
https://www.teagasc.ie/media/website/publications/2018/2--Biomass-and-Heat-pumps.pdf

References

1. Gruda, N., Bisbis, M. & Tanny, J. (2019) Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production–A review. *Journal of Cleaner Production* **225**: 324-339.
2. Dion, L. M., Lefsrud, M. & Orsat, V. (2011) Review of CO2 recovery methods from the exhaust gas of biomass heating systems for safe enrichment in greenhouses. *Biomass and Bioenergy* **35**(8): 3422-3432.
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4. Ahamed, M. S., Guo, H. & Tanino, K. (2019) Energy saving techniques for reducing the heating cost of conventional greenhouses. *Biosystems Engineering* **178**: 9-33.
5. Sánchez-Molina, J. A., Reinoso, J. V., Acién, F. G., Rodríguez, F. & López, J. C. (2014) Development of a biomass-based system for nocturnal temperature and diurnal CO_2 concentration control in greenhouses. *Biomass and Bioenergy* **67**: 60-71.

1. Comprehensive literature review of the main impacts of protected horticulture on GHG emissions and practices for mitigation. Short section summarising key literature on the use of biomass in protected horticulture, with considerations around embedded emissions.

2. Descriptive review of CO_2 recovery from biogas and biomass heating systems for use in protected horticulture. Detailed discussion of the feasibility of biomass fuels from an economic and emissions perspective.

3. Comprehensive literature review of CO_2 enrichment methods in protected horticulture. Includes semi-quantitative comparison of landfill and AD biogas, and multiple types of biomass fuel vs. fossil fuel sources in terms of emissions and purification requirements.

4. Comprehensive literature review investigating techniques to reduce the heating cost of conventional greenhouses. Brief section on the use of biomass with references to economic evaluations and challenges around cleaning for CO_2 enrichment.

5. Overview of the design, installation, and optimisation of a biomass-based heating system at the Las Palmerillas experimental glasshouse facility. Discusses CO2 and heat production from several types of biomass fuel.

10.4.3. North walls (passive heat storage)

Impact summary

North walls are an effective form of passive heat storage, consisting of an opaque wall built along the north side of the glasshouse. The wall is typically made of bricks and/or cement and is often filled with concrete, sand or phase change material (PCM). North walls can also be painted black to promote absorption of heat energy or with a reflective coating to promote reflection of light back onto crops. North walls are most effective when the glasshouse is aligned in an east-west direction. During the day, solar energy that would normally escape through the north side of the glasshouse is captured and stored in the wall material. At night, as the temperature drops, this thermal energy is released back into the glasshouse to increase the air temperature. Installation of a north wall can reduce heat energy use by 35-50% across a range of different glasshouse types and north wall materials.

Effectiveness		
	Reduced net GHG	++
	Other impacts	
	Cost savings	++
	Improved crop management	++
Cost		
		£-££
Speed of change		
		Fast - Moderate
Strength of evidence		
	Quality	3
	Context	2
	Overall	3

Narrative Summary

1. What is the practice?

A north wall is an opaque wall built internally along the north side of an east-west oriented glasshouse (Ahamed et al., 2019). In the northern hemisphere, a large proportion of summer sunlight comes from the south and leaves the glasshouse through the north side. By building an opaque wall along the north side, this heat energy can be trapped and stored, to be released at night when the temperature drops. North walls are typically made of bricks and/or concrete, and filled with water cannisters, sand, phase change material (PCM) or concrete (Berroug et al., 2011). North walls can be painted black to promote heat capture and are often coupled with thermal screens at night.

2. How effective is it?

Ahamed et al. (2019) report heat energy reductions of 35-50% across a range of glasshouses implementing north walls made from bricks coated in concrete. Berroug et al. (2011) describe a case study from France in which a 60cm north wall constructed in a 30 m^2 tomato glasshouse was able to meet 82% of annual heating needs. Two other French studies, as reported by Ahamed et al. (2019), showed increased glasshouse temperatures of 7-9°C versus outside in both 100 m^2 and 340 m^2 sites.

3. Where does it work?

North walls are likely to be most effective in small-scale glasshouses which are on an east-west axis. For large glasshouses, there is likely to be uneven redistribution of heat at night, which could result in quality differences across the crop.

4. How much does it cost?

Costs for installing a non-PCM north wall will be relatively inexpensive, although it is important to weigh up the potential benefits with the cost of lost productive space. PCM requires less space to achieve the same level of thermal storage.

5. How can I do it well?

North walls should be considered in the context of other climate control practices being implemented, including active heating, ventilation and humidity control, as well as the crop type, the external climate and geography, and the size of the glasshouse. There are also many different materials, including bricks, concrete, sand, water and PCM. For non-PCM north walls, the minimum thickness should be 45-60 cm (Berroug et al. 2011), while the use of PCM can enable effective heat storage at just 8 cm, although with higher costs.

6. How strong is the evidence?

There are many examples across several high-quality reviews supporting increased glasshouse temperatures overnight from the use of north wall systems. There are some European case studies in the same reviews that report heat energy savings of 35-50%. This suggests notable potential reductions in GHG emissions due to reduced use of fuels and grid electricity, however there is a significant lack of contextual evidence in the UK to support these findings, particularly in terms of which glasshouse sizes, types and locations would benefit most from north walls. Additionally, there is no literature to date that has evaluated the overall impact on GHG emissions specifically.

7. Where can I find further information?

No relevant resources were identified to provide additional practical information to growers on the use of north walls.

References

1. Sethi, V. P. & Sharma, S. K. (2008) Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications. *Solar Energy* **82**(9): 832-859.

2. Ahamed, M. S., Guo, H. & Tanino, K. (2019) Energy saving techniques for reducing the heating cost of conventional greenhouses. *Biosystems Engineering* **178**: 9-33.

3. Berroug, F., Lakhal, E.K., El Omari, M., Faraji, M. & El Qarnia, H. (2011) Thermal performance of a greenhouse with a phase change material north wall. *Energy and Buildings* **43**(11): 3027-3035.

1. Comprehensive review of technologies for heating and cooling glasshouses, including thermal energy storage options. Meta-analytical comparison of European case studies, with figures for temperature differentials and energy savings.

2. Comprehensive review of techniques for reducing the heating cost of conventional greenhouses. Includes detailed sections on the use of north walls, water storage and rock bed storage.

3. Mathematical modelling study of the impact on temperature and humidity of a PCM north wall in January in Marrakesh. Also contains a comprehensive introduction to different types of north walls and data from several case studies.

10.4.4. Thermal screens

Impact summary

Thermal screens are installed on the inside of the glasshouse to form a false ceiling between the crops and the glasshouse roof. They are made from a variety of materials including aluminium, polyester, polyethylene, and others. Thermal screens protect the crops from cold air falling from above while also preventing heat radiation from leaving through the roof of the glasshouse. The screens are typically installed on mechanical rollers so can be folded away during the day allow increased light into the glasshouse. Thermal screens are a relatively cheap, highly effective method of increasing the average temperature inside the glasshouse which in turn reduces heating requirements and energy use.

Effectiveness	
Reduced net GHG	++
Other impacts	
Cost savings	++
Improved crop management	++
Cost	
	££-£££
Speed of change	
	Fast - Moderate
Strength of evidence	
Quality	3
Context	3
Overall	3

Narrative Summary

1. What is the practice?

Thermal screens, or night curtains, are sheets of material that are installed on the inside of a glasshouse to form a false ceiling. They are installed on mechanical rollers so they can be rolled up during the day to let more light enter the glasshouse. Some thermal screens have light diffusing properties and so may be left open during the day to protect the plants from excess heat and distribute light more evenly (Ahamed et al., 2019). At night, thermal screes protect the plants from cold air falling from the top of the glasshouse and prevent thermal radiation from rising upwards and escaping through the glasshouse roof. There are a range of materials used to make thermal screens, including aluminium, polyester, polyethylene and polypropylene (Sethi & Sharma, 2008).

2. How effective is it?

Thermal screens are an effective way of reducing glasshouse energy use, and therefore GHG emissions. Dieleman & Hemming (2011) found total energy savings from thermal screens of 20-35%, suggesting that 20% was more practical for commercial glasshouses due to conflict with light and humidity requirements. Ahamed et al. (2019) reviewed several studies and found 40-70% reduction in night-time energy loss, and 23-60% reduction in energy used for heating, with one study in a venlo glasshouse in the Netherlands reporting annual total energy reductions of 20% versus without thermal screens.

3. Where does it work?

Thermal screens can be applied to most glasshouses and are likely already in use by the majority of UK growers, as they are an essential element of managing temperature, humidity and light within the crop. Thermal screens can be applied in heated and unheated systems, and the wide range of materials and installations means a varying degree of effectiveness, cost, and level of automation. Thermal screens can be manually controlled or integrated into automated climate control, incorporating temperature, light, and humidity.

4. How much does it cost?

There are many different types of thermal screen and installation costs will vary depending on the material required, installation type, level of automation and the size of the glasshouse. Thermal screens are regarded as a relatively cost-effective measure to reduce energy use in most greenhouses. Cost-savings vary depending on fuel prices, but Sethi & Sharma (2008) reported 30% reduction in energy costs using aluminised polyester thermal screens versus unscreened glasshouse costs.

5. How can I do it well?

The optimum design for a thermal screen system will depend on the crop, the glasshouse design, the degree of automation, thermal screen type and the external climate. While many growers likely use thermal screens already, there is a shortage of contextual evidence describing and evaluating different thermal screen systems, so it is difficult to determine the optimal implementation for a given site and production system. Case studies are needed to comprehensively evaluate different thermal screen systems to determine the best design for a given set of circumstances. Many suppliers will provide a turnkey service for thermal screen design and installation, ensuring that the system is ideally suited to the individual grower's requirements. Thermal screens become even more effective when coupled with thermal energy storage so this is something else that should also be considered.

6. How strong is the evidence?

There is a robust and varied evidence base in support of energy savings (and therefore GHG reduction) from the installation of thermal screens across a range of crop types, glasshouse designs and climates. However, there are no reviews that specifically address thermal screens so this is an area that could be addressed in future research. Bringing together all the information on installation types and energy savings, coupled with information on relevant UK case studies would further optimise the implementation of this practice. Additionally, there are no examples in the literature of investigations into GHG emissions specifically, so this is another knowledge gap that should be addressed.

7. Where can I find further information?

The AHDB GrowSave project provides additional information on a range of aspects of glasshouse energy management and climate control, including the use of thermal screens:
https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/AHDB%20Horticulture%20/EnergyManagement211_WEB.pdf

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1. Comprehensive review of technologies for heating and cooling glasshouses, including thermal screens. Thorough descriptive review of a range of thermal screen materials from European case studies, with figures for temperature differentials and energy savings.

2. Comprehensive literature review investigating techniques to reduce the heating cost of conventional greenhouses. Meta-analytical review of case studies from across the world using a range of different thermal screen materials, with temperature differentials and energy savings.

3. Descriptive review of practices to reduce greenhouse energy use, including climate optimisation techniques and the use of thermal screens. References several studies across a range of production systems with quantified energy savings.

4. Descriptive review of techniques and technologies to enable energy-efficient greenhouse climate control. Specific sections on reducing energy loss using thermal screens, with figures on energy savings from a range of studies.

10.4.5. Optimise climate control

Impact summary

One of the main benefits of protected horticulture is the ability to control the internal environment – particularly the temperature and humidity. The degree of control varies considerably, from solar heating with passive ventilation for cooling and dehumidification, to the use of advanced computer systems in closed greenhouses which utilise real-time data from sensors to ensure optimal growing conditions. Optimising climate control is extremely important for maintaining crop productivity, reducing disease risk, and minimising energy use. There are a range of techniques to do this, including increased use of sensors or automation, temperature integration, and alternative dehumidification systems, all of which can complement other energy-saving practices.

Effectiveness		
	Reduced net GHG	+
	Other impacts	
	Cost savings	+
	Improved crop management	++
Cost		
		£-££
Speed of change		
		Moderate
Strength of evidence		
	Quality	3
	Context	2
	Overall	2

Narrative Summary

1. What is the practice?

Climate control optimisation involves a range of techniques that contribute to an optimal internal climate for crop growth, while using as little energy as possible. This could be investment in automated climate control systems if none are in place, improved sensors or automation, improved air circulation, temperature integration or better humidity control. Temperature is one of the most important aspects of climate control, as it directly affects crop growth and has implications on humidity control and air circulation. One method of reducing energy use associated with temperature control is through temperature integration (Ahamed et al., 2019). This relies on the principle that most glasshouse crops are relatively insensitive to moderate temperature fluctuations and instead respond to the average daily temperature. Temperature integration is the process of increasing the heating set-point when conditions are favourable and lowering it when losses are high (within limits), to ensure an optimal average temperature while reducing energy use. For example, high wind speed causes heat to be lost at a greater rate, so when it is windy, the temperature set-point should be lowered. When wind speed reduces, the temperature set-point is increased again to maintain the daily average. Humidity is also crucial within the glasshouse for optimal production and to reduce disease risk (Amani et al., 2020). Dehumidification is typically done via heating and/or ventilation, which is often expensive in terms of energy use, particularly in colder climates. There are a wide range of dehumidification technologies available, including natural convection condensation, heat pump dehumidifiers, air-to-air heat exchangers and desiccants, many of which can increasingly be powered by renewable sources. Poor air circulation within the glasshouse creates areas of low CO_2, high humidity and variation in temperature. These areas can be identified via advanced sensors such as infrared cameras, which can distribute heat more effectively throughout the glasshouse and potentially save energy.

2. How effective is it?

Temperature integration has been shown to reduce heating energy consumption by 30% in winter greenhouses at various locations (Ahamed et al., 2019). In a Canadian study, Han et al. (2015) observed that heat pump dehumidification was more energy-intensive than air-to-air heat exchangers but resulted in lower overall energy use due to warm air being recovered. There is however a lack of contextual evidence in the UK, particularly for large-scale glasshouses. The use of advanced sensors and computer systems to regulate the internal glasshouse climate likely has benefits for energy use and GHG emissions, although no academic studies have reviewed the latest developments in sensors or control systems.

3. Where does it work?

Most glasshouses have some form of climate control, whether it be highly automated using precision sensors or manually using natural ventilation and irrigation. This is primarily for crop management purposes, to increase yield and quality, and reduce disease risk. Where glasshouses are heated or use active ventilation or irrigation for cooling, the optimisation of climate control will also reduce unnecessary energy use. Even in relatively passive production systems, improvements in climate control are likely to improve yields and reduce wastage, which will also have an impact on overall emissions per unit of production.

4. How much does it cost?

Most of the techniques described in this narrative summary involve adjusting existing systems and process, and should result in a net reduction in costs associated with reduced energy use. Where novel sensors or climate control systems are introduced, these will incur additional costs, although there are a wide range of different systems, suited to different glasshouse systems so the costs will vary depending on the individual situation.

5. How can I do it well?

Each production system has different capabilities and requirements in a climate control system, depending on the size of the operation, the amount of capital available, the external climate etc. There is a great deal of technical information available that discusses the practical implications of various aspects of climate control, such as the AHDB GrowSave project (AHDB, 2019d). There is a lack of UK case studies to demonstrate the benefits of different climate control techniques in specific contexts. One of the challenges of climate control is that it is composed of several interacting factors: light, temperature, humidity, carbon dioxide, and air flow. It can difficult to balance conflicting parameters which is an advantage of computer-controlled systems – they can manage complex interacting environmental conditions to get the overall best result. Where computer-controlled systems are not used, it is still beneficial to understand the interactions between the different elements of climate control, as it will make for more effective management of the crop environment and reduce energy costs.

6. How strong is the evidence?

The complex inter-related relationship between different elements of climate control makes it difficult to assess individual practices. Temperature integration has variable evidence, but the consensus is that it can reduce energy costs without impacting crop growth, at least in some crop types and production systems (i.e. those that are less sensitive to temperature fluctuations). Dehumidification techniques that reduce ventilation (and therefore heat loss) have been shown to be effective in one case study in Canada, although more evidence is required in the UK context. Overall, there is a lack of UK case studies that detail the specific components of a climate system for a given crop and production system.

7. Where can I find further information?

The AHDB GrowSave project provides additional information on a range of aspects of glasshouse energy management and climate control:
https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/AHDB%20Horticulture%20/EnergyManagement211_WEB.pdf

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2. Descriptive review of techniques and technologies to enable energy-efficient greenhouse climate control. Specific sections on reducing energy loss through ventilation and other cooling systems.

3. Comprehensive literature review investigating techniques to reduce the heating cost of conventional greenhouses. Brief section on the use of biomass with references to economic evaluations and challenges around cleaning for CO_2 enrichment.

4. Descriptive review of practices to reduce greenhouse energy use, including temperature optimisation, humidity control, and renewable fuels. References some studies which provide figures for energy savings.

5. Evaluation of air-to-air heat exchangers and mechanical refrigeration dehumidifiers vs. conventional exhaust ventilation system across a year in a commercial Canadian tomato glasshouse.