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Abstract

The efficiency of Ireland’s grass-based livestock systems can be attributed to high outputs, low production costs and a low carbon footprint relative to housed systems. Methane (CH₄) is a potent greenhouse gas (GHG) of which enteric fermentation from livestock production is a key source, being directly responsible for 57% of Irish agricultural GHG emissions. There are a number of strategies including dietary manipulation and breeding initiatives that have shown promising results as potential mitigation solutions for ruminant livestock production. However, the majority of international research has predominantly been conducted on confined systems. Given the economic viability of Irish livestock systems, it is vital that any mitigation methods are assessed at pasture. Such research cannot be completed without access to suitable equipment for measuring CH₄ emissions at grazing. This review documents the current knowledge capacity in Ireland (publications and projects) and includes an inventory of equipment currently available to conduct research. A number of strategic research avenues are identified herein that warrant further investigation including breeding initiatives and dietary manipulation. It was notable that enteric CH₄ research seems to be lacking in Ireland as it constituted 14% of Irish agricultural GHG research publications from 2016 to 2021. A number of key infrastructural deficits were identified including respiration chambers (there are none currently operational in the Republic of Ireland) and an urgent need for more pasture-based GreenFeed™ systems. These deficits will need to be addressed to enable inventory refinement, research progression and the development of effective solutions to enteric CH₄ abatement in Ireland.

Keywords

Abatement • livestock • methane • research • sustainability

Introduction

Although methane (CH₄) has a relatively short atmospheric residence time (half-life of 9.1 yrs), it is a potent greenhouse gas (GHG) with 84 times the global warming potential (GWP) of carbon dioxide (CO₂) over its atmospheric residence time and 28 times that of CO₂ over a 100-yr time horizon (GWP100) (IPCC, 2014). Methane is the second-largest contributor to anthropogenic climate change with global emissions estimated at 559 [540–568] Tg CH₄/yr for the decade 2003–2012 (Saunois et al., 2016). The principal anthropogenic sources are fossil fuel extraction and burning, with biogenic contributions associated with eructation from ruminants during fermentation of feed, management of organic wastes and manures and rice paddy cultivation (IPCC, 2014). In 2019, agriculture was responsible for 35.5% of Ireland’s GHG emissions, of which enteric CH₄ comprised 57.45% (EPA, 2021).

Agricultural GHG emissions belong to the non-emissions trading sector (non-ETS), meaning that emissions from the sector are not subject to the European Union cap and trade system. This also means that national governments, rather than EU, are directly responsible for emission reductions in these sectors with the extent of each country’s reductions established under the 2030 Effort Sharing Regulation (ESR) (PE/3/2018/REV/2). Under the ESR, Ireland is obliged to reduce non-ETS GHG emissions by 30% relative to 2005 over the 2021–2030 commitment period. This will require agriculture to limit emissions to between 17.5 and 19 million tonnes CO₂ equivalent, while also establishing a downward trajectory to reach net zero emissions by 2050. In order to identify pathways for emissions reductions, a marginal abatement cost curve (MACC) analysis was conducted to

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establish the potential mitigation capacity of the Agriculture, Forestry and Other Land-use (AFOLU) sectors and the associated costs (Lanigan et al., 2018). While other GHG such as nitrous oxide have been well researched regarding point sources and mitigation methods (Harty et al., 2016; Krol et al., 2016), there are many unanswered questions regarding the development of a suitable Irish CH₄ abatement strategy. Therefore, the specific aims of this review are: (1) to identify and critically review CH₄ mitigation strategies that may be offer promise as successful CH₄ mitigation strategies. Dietary regimes and animal selection are promising CH₄ mitigation strategies as both dietary management (Carberry et al., 2014; Henderson et al., 2015; Lyons et al., 2017; Liu et al., 2019; Smith et al., 2020a) and host genetics (Weimer et al., 2010; Henderson et al., 2015; Rohe et al., 2016; Li et al., 2019) have been demonstrated to alter rumen microbial composition. **Methods for measuring methane** The main methods to measure CH₄ emissions from ruminants include: (1) respiration chambers (RCs); (2) portable digest feed (Tapio et al., 2017). The majority (87%) of enteric CH₄ is eructated from the forestomach (rumen). A smaller proportion (13%) originates in the hindgut where it is absorbed into the blood and exhaled from the lungs (Hammond et al., 2016). Fermentation is carried out by a complex anaerobic microbial ecosystem, consisting of bacteria, archaea, protozoa and fungi, in the forestomach (rumen) of ruminant livestock (Huws et al., 2018). Individual members of the rumen microbial community play a key role in the fermentation of complex plant structures, and subsequent supply of nutrition, for the ruminant host. Indeed, during enteric (rumen) fermentation, ingested feed is converted into volatile fatty acids (VFA), which provide an estimated 63% of the ruminant animal’s energy requirements (Bergman, 1990). In addition to the supply of VFA to the ruminant host, rumen microbial fermentation yields carbon dioxide (CO₂) and hydrogen (H₂) as metabolic end-products (Newbold & Ramos-Morales, 2020). The production of CH₄, methanogenesis, acts as a H₂ sink in the rumen, which facilitates the progression of further fermentation by preventing an accumulation of excess H₂ which may otherwise hinder electron transport (Morgavi et al., 2010). Methanogens, belonging to the kingdom archaea, are the sole producers of CH₄ in the rumen with the majority of enteric CH₄ believed to originate from the hydrogenotrophic methanogenesis pathway (Equation 1), whereby CO₂ is reduced by H₂ (Janssen & Kris, 2008). Finally, the majority of CH₄ originating from ruminant livestock is expelled, to the atmosphere, via the breath of the animal (Hammond et al., 2016). **Methods for measuring methane** The main methods to measure CH₄ emissions from ruminants include: (1) respiration chambers (RCs); (2) portable digest feed (Tapio et al., 2017). The majority (87%) of enteric CH₄ is eructated from the forestomach (rumen). A smaller proportion (13%) originates in the hindgut where it is absorbed into the blood and exhaled from the lungs (Hammond et al., 2016). Fermentation is carried out by a complex anaerobic microbial ecosystem, consisting of bacteria, archaea, protozoa and fungi, in the forestomach (rumen) of ruminant livestock (Huws et al., 2018). Individual members of the rumen microbial community play a key role in the fermentation of complex plant structures, and subsequent supply of nutrition, for the ruminant host. Indeed, during enteric (rumen) fermentation, ingested feed is converted into volatile fatty acids (VFA), which provide an estimated 63% of the ruminant animal’s energy requirements (Bergman, 1990). In addition to the supply of VFA to the ruminant host, rumen microbial fermentation yields carbon dioxide (CO₂) and hydrogen (H₂) as metabolic end-products (Newbold & Ramos-Morales, 2020). The production of CH₄, methanogenesis, acts as a H₂ sink in the rumen, which facilitates the progression of further fermentation by preventing an accumulation of excess H₂ which may otherwise hinder electron transport (Morgavi et al., 2010). Methanogens, belonging to the kingdom archaea, are the sole producers of CH₄ in the rumen with the majority of enteric CH₄ believed to originate from the hydrogenotrophic methanogenesis pathway (Equation 1), whereby CO₂ is reduced by H₂ (Janssen & Kris, 2008). Finally, the majority of CH₄ originating from ruminant livestock is expelled, to the atmosphere, via the breath of the animal (Hammond et al., 2016). **Methods for measuring methane** The main methods to measure CH₄ emissions from ruminants include: (1) respiration chambers (RCs); (2) portable

### The process of enteric methane production

Enteric CH₄ originates as a by-product of rumen microbial fermentation, the process through which ruminant livestock...
Table 1: Summary of methane measurement equipment and associated cost, advantages and disadvantages

| Method                        | Advantages                                                                 | Disadvantages                                                                 | Approximate cost                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Respiration chambers          | Measures all CH₄ emissions from the animal                                  | Does not represent field or grazing patterns                                   | €50,000–€60,000 per chamber including individual air-conditioning, gas meters and associated devices |
| SF₆                           | Measures CH₄ at pasture                                                    | Large variability and difficult to maintain at pasture                         | – €10,000 for 20 sets. Equipment include individual measurement sets including canisters, absorption pipes (excluding gas chromatography techniques and pump required for analyses) |
| GreenFeeds                    | Measures CH₄ at both indoor and at pasture                                 | Potential bias due to animal behaviour                                         | €65,000 per unit for indoor systems (up to €125,000 in total for additional costs of adding trailers for pasture-based systems) |
| Portable accumulation chambers (sheep) | High levels of correlation with RC                                        | Artificial environment for the animal which can cause stress.                  | – €80,000 per chamber including individual air-conditioning, gas meters and associated devices |
|                               | Quick measurements cause less stress on the animal                         |                                                                                   |                                                                                  |
|                               | Easy to operate                                                            |                                                                                   |                                                                                  |

Accumulation chambers (PACs) (for smaller livestock); (3) GreenFeed™ (GF) systems; and (4) the sulphur hexafluoride tracer technique (SF₆). Respiration chambers have been used to estimate energy losses and CH₄ emissions from livestock for over a century (Hammond et al., 2016). The underlying principles of the RC involves keeping an animal in a pressurised chamber, with the enteric emissions of the animal estimated as the difference in the concentration of gases entering and leaving the chamber, with the fluctuation in gas concentrations assumed to be those emitted from the animal (eructated, exhaled and flatulence) (Storm et al., 2012). The experimental time period may vary but is typically ~96 h (Muñoz et al., 2012). Emissions are determined as the difference in CH₄ gas concentrations entering and leaving the chamber with and corrected for temperature, humidity and pressure. RCs are considered the “gold standard” for recording CH₄ measurements due to high levels of repeatability, robustness and precision (Gardiner et al., 2015; Patra, 2016). However, animals are required to be contained within a standardised chamber for the experimental period. Therefore, the method is unsuited to estimating emissions from animals under grazing conditions. One of the main disadvantages to RC is the changes in the behaviour of contained animals and DMI can drop, meaning in-chamber CH₄ measurements may not reflect actual animal CH₄ output (Table 1). Portable accumulation chambers act as airtight chambers that measure CH₄ and CO₂ emissions from small animals such as sheep (Image 1). This method is considered a rapid (1 h), straightforward and highly sensitive method.
Effective technique as results show high comparability with RC results (Goopy et al., 2016; Jonker et al., 2018). However, PAC cannot be deployed for longer periods as increased CO₂ concentration can negatively influence measurements, thus PAC only allows for measurements over a single time point (Hammond et al., 2016). Breath sampling during feeding can be analysed through GreenFeed™ (GF) systems. They operate as open-circuit head-chambers baited with feed pellets to attract the animal. Airflow inside the feed trough is collected via an extractor fan, with the analyses of CH₄ and CO₂ fluxes determined with the use of infra-red sensors, allowing for the calculation of CH₄ concentration (Hristov et al., 2015; Huhtanen et al., 2015; Jonker et al., 2016). GreenFeed™ units can also be fitted with sensors to measure H₂, O₂ and H₂S. The accuracy of CH₄ measurements, obtained with the use of the GF system, can potentially be compromised, if visitation to the unit is not reflective of the diurnal pattern of enteric emissions (Hristov et al., 2018). As a result, it is imperative animals are permitted access to the unit at even intervals throughout a 24-h period over the duration of the measurement period. Feeding of bait to attract the animal to the GF may also cause issues, for example, if investigating forage diets, feeding concentrate feed may impact on the results. Similarly, if the cattle are on an ad libitum concentrate diet, they may not visit the GF unit and training the animals may be difficult (Table 1). GreenFeed™ systems are not restricted to housed environments and have been successfully used to measure CH₄ emissions on intensive pasture-based dairy systems (Waghorn et al., 2016). Although GFs have been used primarily on cattle to date, there has been development of systems for use with sheep and calves (Nguyen et al., 2018; Meale et al., 2021). Another breath sampling method termed “the sniffer technique”, where a gas sampling inlet is placed within the feed manger of a robotic milking unit, measures CH₄ emissions from the animal at milking events. From these measurements, the daily emission rates can be determined. However, as the sniffer technology has primarily been developed for assessing the methanogenic output of dairy cows at milking (Garnsworthy et al., 2012), its use within a pasture setting, to estimate emissions from non-lactating ruminants, is limited.

The SF₆ technique involves placing a small permeation tube containing SF₆ inside the rumen, and collection tubes with sample lines are used to collect breath samples from the animal. This allows the CH₄ emission rate to be calculated from the known SF₆ emission rate and the measured SF₆ and CH₄ concentrations (Johnson et al., 1994). The use of SF₆ is a labour-intensive method for measuring CH₄ as it involves daily gas canister collections, some loss of canisters from animals and animal handling issues (Table 1). In a comparative study by Deighton et al. (2013), it was reported that prolonged deployment of SF₆ tubes can result in an overestimation of CH₄ emissions from animals if the declining release rate of SF₆ from permeation tubes over time is not accounted for. Additionally, Hristov et al. (2016) found higher variability of results generated by the SF₆ technique compared to the GF method. The comparative study by Garnsworthy et al. (2019) found that all methods are highly correlated with RC, but levels of correlation between non-RC methods are lower. Although Jonker et al. (2016) found no difference between average emission yields from the SF₆ technique, the GF system or from those of RC, there are benefits and drawbacks associated with all methods. Additionally, correcting CH₄ emissions for either intake or output can provide a more contextualised comparison between individual animals than daily emissions alone (outlined in section 1). In order for such calculations to be made, individual feeding units for use in housed systems and during experiments are vital to determine the total feed intake and DMI associated with CH₄ output.

Mitigation strategies – farm efficiency

O’Brien & Shalloo (2016) recommended a number of on-farm efficiency measures that can aid in reducing CH₄ emissions from Irish livestock production systems such as extending the length of the grazing season, increasing the daily live weight gain of beef cattle and lambs, optimising the age and rate of calving and lambing, and reducing the age at slaughter. Such strategies are complementary and when used in conjunction can provide effective CH₄ emissions savings. Albeit, these measures only confer a benefit on a short-term basis and at fixed livestock numbers as increasing the stocking rate will increase overall emissions. Livestock breeding initiatives are an effective farm management practice that can aid in CH₄ mitigation in a number of ways including the following: (1) breeding more productive animals can reduce emission intensity (less CH₄ emissions per unit milk/meat produced), for example, increasing dairy cow genetic merit via the EBI and therefore milk production; (2) breeding for increased health, fertility and productivity, that is, faster-growing animals reduces the age at slaughter and thus cumulative CH₄ emissions over the animal’s lifespan; and (3) selecting for more CH₄-efficient traits in animals, which will in turn reduce overall CH₄ emissions. Regarding the latter, there are a number of studies, particularly in New Zealand, which highlight the association between the rumen microbiome, genotype and phenotype of sheep bred for low CH₄ output (Xiang et al., 2016; Jonker et al., 2019a; Rowe et al., 2020). Goopy et al. (2014) found that certain physical traits are associated with sheep selectively bred for low CH₄ output, with such animals having smaller rumens and a shorter rumen retention time. In the study by Smith et al. (2021), cattle ranked low for residual CH₄ output (difference between animals predicted, and actual level of CH₄ output, based on DMI and body weight) had an ∼30% reduction in daily CH₄ emissions and emissions intensity (g/kg of carcass weight) in comparison...
to their high residual CH$_4$ counterparts. In addition, the previous authors noted feed intake and animal performance were not compromised by residual CH$_4$ output ranking. Although it can be slow to select for such low-emitting animals, nevertheless, such breeding strategies offer a long-term, highly effective solution to CH$_4$ abatement (González-Recio et al., 2020).

**Mitigation strategies – dietary manipulation**

Dietary manipulation involving additives and feed/sward type are of fundamental importance in CH$_4$ mitigation strategies as emissions are highly correlated to animal feed intake and digestibility. Thus, dietary manipulation (i.e. changing the amount or proportion of carbohydrate, protein and roughage in animal diets) has been previously explored by numerous studies and remains an important avenue of further investigation.

**Feed additives**

Historically, halogenic compounds such as bromoform and chloroform have been studied for their efficacy as anti-methanogenic compounds (Bauchop, 1967; Russel & Martin, 1984). At present, such compounds are mainly used as experimental controls (Martínez-Fernández et al., 2018) due to their strong anti-methanogenic albeit toxic and carcinogenic qualities. This has also been the case for ionophores such as monesin (an antibiotic) which deplete the rumen microbiome and therefore methanogenesis. Antibiotics were previously fed to animals as growth promoters, particularly in the USA. However, since 2006, the use of ionophores is prohibited within the EU due to issues with resistance and human health concerns (EC, 2005). Hristov et al. (2013) list the efficacy of various livestock dietary additives for reducing CH$_4$ emissions. Their study highlights the efficacy of including seaweed in ruminant diets to substantially reduce CH$_4$ emissions. It has been found that certain seaweeds, particularly red and brown species such as Asparagopsis taxiformis (red) and Sargassum flavidicans (brown), contain compounds with anti-methanogenic properties as outlined in Abbott et al. (2020). Bromoform (a haloform mostly found in red seaweeds) is known to inhibit the enzymes involved in methanogenesis. Various other compounds found in seaweeds such as lipids, peptides and phlorotannins also play a role in reducing CH$_4$ emissions, although the modes of action are less understood (Machado et al., 2016; Abbott et al., 2020). Many studies have seen significant reductions in CH$_4$ emissions from livestock receiving seaweed-based additives at various administration rates and concentrations (Machado et al., 2016; Li et al., 2018; Roque et al., 2019; Kinley et al., 2020; Roque et al., 2021). However, there are concerns surrounding the potential for compounds such as iodine (toxic at high levels) and bromoform (carcinogen) to carry through the food chain and adversely affect human health (Antaya et al., 2019; Abbott et al., 2020). Additionally, importing tropical seaweed species such as A. taxiformis risks negatively impacting bioactive compounds during transit. There are also monetary costs and risk of “pollution swapping” through increased GHG emissions associated with transport. The supply of native seaweeds (such as temperate brown species) could present issues, for example, harvesting wild crops or commercially growing seaweeds could have negative environmental impacts. To date, seaweed has not been tested in Irish pasture-based production systems as an anti-methanogenic additive. Overall, further work will be required to understand the potential long-term effects of seaweed additives on animal productivity and human health.

The addition of fats and oils as CH$_4$ abatement compounds to ruminant diets has shown promising results. Lipids can reduce CH$_4$ emissions, as they are toxic to and therefore reduce methanogens and protozoan numbers within the rumen (Beauchemin et al., 2009; Broucek, 2018). Overall, results from lipid addition have been variable, but up to 20% reduction in emissions have been reported (Beauchemin et al., 2020). However, fat addition can negatively affect animal feed intake, carbohydrate digestion in the rumen and overall milk quality. As regards plant-based oil seeds, Kliem et al. (2019) found only linseed-based supplements reduced CH$_4$ emissions (across production, yield and emissions intensity) when comparing the administration of linseed, palm and rapeseed oil products to dairy cows. Similarly, Boland et al. (2020) reported an 18% decrease in emissions intensity (g CH$_4$/kg milk) from pasture-fed dairy cows receiving linseed oil-based concentrates compared with cows receiving stearic acid or soy oil-based concentrates.

There are a range of industrially formulated products with the potential to reduce methanogenesis such as Mootral (a feed additive containing allicin from garlic and citrus extracts) and Agolin Ruminant (an essential oil blend). Studies have shown positive, albeit variable, effects of both products on reducing the amount and rate of enteric CH$_4$ production in both dairy and beef cattle (Castro-Montoya et al., 2015; Hargreaves et al., 2019; Belanche et al., 2020). Agolin Ruminant is an affordable solution that has also been shown to improve livestock productivity (particularly dairy), which can reduce CH$_4$ emission intensity. However, both of these additives have primarily been tested as part of total mixed ration (TMR) diets and are in need of testing at pasture level.

The synthetic, non-toxic, organic compound 3-nitrooxypropanol (3-NOP) has proven to be an effective feed additive for the reduction of enteric CH$_4$ emissions (up to 30% reductions), without compromising animal performance. 3-NOP inhibits methane formation by binding with the enzyme methyl-coenzyme M reductase (MCR) (the catalyst for methane formation) during the final stages of methanogenesis (Meale et al., 2021).
efficacy of 3-NOP has been assessed in multiple experimental trials (Romero-Perez et al., 2015; Jayanegara et al., 2018; Martinez-Fernandez et al., 2018; Vyas et al., 2018; McGinn et al., 2019; van Gastelen et al., 2020). The recent study of Meale et al. (2021) found that a daily oral administration of 3-NOP to dairy calves from birth to 3 wks post-weaning (14 wks of age) significantly reduced daily CH₄ emissions up until at least 1 yr of age. It is likely that this early-life administration imprinted on the rumen microbiome, which resulted in lasting alterations of the methanogenesis process. Similar reductions in CH₄ emissions from adult cattle receiving 3-NOP have not shown long-term persistence once administration ceased as reported in the study on housed beef cattle by Romero-Perez et al. (2015). Most 3-NOP studies have been carried out on indoor/confined systems; however, beneficial results are harder to achieve at pasture level as additives such as 3-NOP need to be combined within animal feed or administered directly after feeding. Therefore, the development of suitable technologies such as slow-release boluses will be required for pasture-based administration as direct feeding cannot take place outside housed periods (Leahy et al., 2020). Additionally, consumer behaviour will need to be considered before 3-NOP or other synthetic additives are adopted as a mitigation option, that is there may be issues surrounding the consumption of products that arise from animals fed on synthetic compounds (Beauchemin et al., 2020).

Sward type
In Ireland, cattle consume >80% of their DMI requirement from grassland forage (O’Brien et al., 2018) with the majority of improved pastures consisting of perennial ryegrass (Lolium perenne L.) monocultures. In recent years there has been increased interest in the use of multi-species swards (a forage mixture consisting of two or more species from different functional groups) for livestock production. This is due to the associated multi-functional benefits which include increased agronomic productivity, livestock health benefits, drought resilience and environmental benefits (Haughey et al., 2018; Grace et al., 2019; Suter et al., 2021). Legumes including white clover (Trifolium repens L.) are often used in multi-species swards and have been shown to contain high tannin levels (Woodfield et al., 2019). Recently, Ku-Vera et al. (2020) presented the potential of plant secondary metabolites such as tannins to modify the rumen microbiome and its function. Stewart et al. (2019) also found that hays with high tannin content have the potential to reduce enteric CH₄ emissions from beef cattle. It has been found that tannins can lower CH₄ emissions through a reduction in fibre digestion (which decreases H₂ production), and by inhibiting the growth of methanogens (Naumann et al., 2017; Jafari et al., 2019). However, Patra & Saxena (2010) recommend that the proportion of tannin in the diet does not exceed 50 g/kg DMI to avoid negative implications on animal performance. It is also worth noting the role of pasture management in CH₄ mitigation with animals grazing on low pre-grazing herbage mass swards having reduced CH₄ emissions intensity due to increased forage digestibility (Wims et al., 2010; Boland et al., 2013). The benefits of white clover on animal performance could potentially impact CH₄ emissions intensity, that is, increased milk yield/solids (Lee et al., 2004; Egan et al., 2017; Dineen et al., 2018) but with the same/lower level of CH₄ output. White clover also increases the passage rate through the rumen which can impact methanogens (Dewhurst et al., 2003; Smith et al., 2020a). Research has also been conducted on legume species other than white clover; Huyen et al. (2016a,b) found that Sanfoin (Onobrychis vicifolia), a tanniniferous legume forage) inclusion within the diet of dairy cows at 50% silage proportion significantly reduced CH₄ emissions intensity. Aside from emissions intensity, Montoya-Flores et al. (2020) found a significant decrease in daily CH₄ emissions from cattle fed high legume (Leucaena leucocephala) proportion diets. Herbaceous species Cichorium intybus and Plantago lanceolata contain high levels of bioactive compounds, in particular condensed tannins (Totty et al., 2013; Peña-Espinoza et al., 2018; Ineichen et al., 2019). A multi-species mixture of sorrel (Rumex acetosa), ox-eye daisy (Leucanthemum vulgare), yarrow (Achillea millefolium), knapweed (Centaurea nigra) and ribwort plantain (Plantago lanceolata) fed as haylage resulted in a 10% reduction in Yₘ (SF₆ technique) compared with a perennial ryegrass monoculture (Hammond et al., 2014). Wilson et al. (2020) reported no CH₄ mitigation effects when lactating dairy cows were fed legume or herb-rich swards, compared to grass-based swards. Jonker et al. (2019b) reported elevated Yₘ for cows fed a diverse sward (containing ryegrasses, [both Lolium perenne and Lolium multiflorum], white clover, lucerne, chicory and plantain) compared to a ryegrass (L. perenne and L. multiflorum) and white clover mixture. Similarly, Loza et al. (2021) found that CH₄ emissions per kg energy corrected milk produced (emissions intensity) to be 11% higher from dairy cows grazing diverse mixtures compared to grass-clover swards. The aforementioned studies present some contrasting results. However, verifying the effect of multi-species swards and different types of species at grazing will be important to determining solutions to CH₄ abatement in Ireland.

Methodology
We undertook a comprehensive literature survey of recent (2016–2021) research publications that focus on enteric CH₄ emissions and rumen microbiome function. This was performed through online searches of relevant databases (SCOPUS and Scholar) using specific key words (“rumen”
AND “livestock” OR “methane” OR “microbiome”). The search was limited to research articles from Irish and Northern Irish research-performing organisations (RPOs). In addition, further relevant published scientific articles were identified from cited references in relevant review or meta-analysis papers including Waters et al. (2020). The relevant papers were added to an excel sheet and the methodology sections were analysed to determine the equipment and methodology used. Contact was then made with the corresponding authors of relevant publications to identify current projects and facilities. The proposals of the main Irish CH4 research projects were also evaluated to determine the facilities and equipment available for use. Site visits to the relevant research centres took place where CH4 projects, research infrastructure and facilities were documented. The current Irish bovine and ovine GHG inventory methodologies were reviewed according to the United Nations Framework Convention on Climate Change (UNFCCC, 2021) Irish National Inventory Reports.

**Results**

**Global warming potential and inventory**

The current metric used to assess the impact of individual gases towards climate change is termed the GWP of CH4 which is “GWP100”. This method equates one GHG unit to its CO2 equivalent, averaged over a 100-yr time horizon. This results in a GWP of 28 in the case of CH4 (IPCC, 2014). However, this method fails to account for the short-lived atmospheric persistence of CH4 (9.1 yrs) relative to other GHGs such as N2O, which persists in the atmosphere for more than 100 yrs and CO2, which has a residence time of several centuries. This means that whilst CH4 has a strong radiative forcing impact when first emitted, this warming impact diminishes as CH4 oxidises to CO2 and H2O. Therefore, there are concerns that the GWP100 overestimates the contribution of CH4 to long-term radiative forcing (Allen et al., 2016; Allen et al., 2018). In terms of CH4 inventory accounting, sheep are currently reported using Tier 1 methodologies in the Irish National Inventory (UNFCCC, 2021). However, there are data available on Irish sheep populations, finishing ages, concentrate usage, housing periods and manure storage systems which could potentially be utilised in the progression to Tier 2 methodologies (O’Brien & Shalloo, 2016). Ireland currently uses Tier 2 inventory estimation for cattle, which disaggregates enteric and manure CH4 emissions from the bovine herd between numerous categories as described in O’Mara (2006). The principal subdivisions are made between dairy and non-dairy (beef) animals. Dairy is subsequently divided in terms of calving date and region with a separate category for dairy heifers. The non-dairy herd is partitioned in terms of suckler cows (subdivided as per dairy cows) and heifers, with bovines for finishing classified based on age and gender. Future developments for reporting of CH4 emissions and incorporating mitigation may require a Tier 3 or modelling approach. Dynamic models based on the mathematical modelling of rumen processes have the potential to incorporate a myriad of feed strategies such as carbohydrate, protein, fat and fibre metabolism. Such models have been simulated in detail and incorporated into US, Dutch and French inventories (Keubreab et al., 2008; Bannink et al., 2011; Eugène et al., 2019). These models are complex and must describe both the dynamics and interactions between various substrate pools and microbial pools and the consequences for the end-products of fermentation. Turnover rates between different pools are generally based on enzyme kinetics and degradation characteristics of different feed types.

As outlined by O’Brien & Shalloo (2016), there is potential to develop Tier 3 inventories for cattle. Data gathered and held by the CSO, Teagasc NFS, Bord Bia and the animal feed industry could potentially be integrated into the development of more accurate, Tier 3 CH4 emission factors for cattle. There is already an extensive body of work on the variation in forage quality on production (Hart et al., 2009; Muñoz et al., 2016). Therefore, the national data required for inputting into a Tier 3 system are already available.

**Irish enteric methane research to date**

Over the last 5 yrs (2016–2021), 14% of Irish agricultural GHG research publications have been based on enteric CH4 emissions (Figure 1). In total, 43 research papers have been published on studies using methodologies such as RCs, SF6 (Images 2 and 3), RUSITEC in vitro rumen simulation and 16S rRNA amplicon sequencing (Table 2). Work carried out in Ireland, which furthers the understanding of the rumen microbiome, include the study by Kumar et al. (2018) and reviews by Huws et al. (2018) and Leahy et al. (2019). A number of studies have investigated strategies for decoupling enteric CH4 emissions from livestock production. The studies by Popova et al. (2017), Smith et al. (2020b) and Boland et al. (2020) examine the effects of dietary supplementations, that is, linseed oil and industrial by-products. Other dietary manipulations strategies including sward composition, sward N application, concentrate type and protein content have been assessed (Hynes et al., 2016; McDonnell et al., 2016; Zhao et al., 2016; Günal et al., 2019; O’Connor et al., 2019; Ferris et al., 2020; Smith et al., 2020a). There have been a number of studies that focused on the genetic selection for production efficiency and low CH4 output animals. The traits investigated include phenotype, age and breeding index of cattle (Morrison et al., 2017; Rubino et al., 2017; Quinton et al., 2018; Ferris et al., 2020). Additionally, there has also
Figure 1. Research publications from Irish and Northern Irish research-performing organisations (2016–2021) that focus on agricultural greenhouse gases (GHGs): nitrous oxide, ammonia (pollutant and indirect GHG), carbon (soil organic carbon (SOC) and forest C) and methane (enteric and non-enteric).

Image 2. SF₆ equipment on grazing sheep, Teagasc, Athenry, Co. Galway.
been Irish involvement with international enteric CH$_4$ database and model development (Niu et al., 2018).

Current research projects in Ireland

There are currently a number of projects focusing on CH$_4$ abatement underway in Ireland (Table 3). Both EU-funded projects, RumenPredict (ERA-GAS) and MASTER (Horizon 2020 – European Commission), have members of Teagasc, University College Dublin (UCD) and the Irish Cattle Breeding Federation (ICBF) working in collaboration to better understand the link between the rumen microbiome composition and CH$_4$ output. There are a number of other ERA-GAS-funded projects including SeaSolutions, a Teagasc co-ordinated project which aims to determine the potential of seaweeds to reduce enteric CH$_4$ emissions from sheep, beef and dairy cattle, METHlab which focuses on the use of lactic acid bacteria as an approach to reduce CH$_4$ emissions from ruminant livestock and GrassToGas which aims to identify individual animal, feed and environmental attributes associated with feed and water intake efficiency for pasture-based sheep production systems using portable accumulation chambers (Image 1). The Teagasc-led Department of Agriculture, Food and the Marine (DAFM)-funded Meth-Abate project seeks to develop new technologies to reduce enteric CH$_4$ emissions from ruminants and emissions from stored manure and slurry. This project is focused on investigating the potential of feed and slurry additives as CH$_4$ mitigation solutions. Meth-Abate has research partners from National University of Ireland, Galway (NUIG), Teagasc, Agri-Food and Biosciences Institute (AFBI), Queens University as well as a number of industry stakeholders. Greenbreed (DAFM funded) is a collaborative project between UCD, Teagasc and the ICBF which aims to determine strategies for the breeding of more CH$_4$-efficient animals. There are a number of GF systems in place at the confinement facilities at the ICBF used to carry out this research (Images 4 and 5). VistaMilk is an Science Foundation Ireland (SFI) research centre, with the aim to “facilitate the development and deployment of new knowledge, new technologies and new decision support tools to maximise the efficiency and effectiveness of the entire dairy production chain”. VistaMilk funds a number of projects investigating feed additives at pasture in dairy cattle at Teagasc, Moorepark (Image 6). APC microbiome is also an SFI-funded centre which has links with CH$_4$ abatement projects such as METH-lab. SMARTSWARD (DAFM funded) is a collaborative project between UCD, TUD and AFBI and is investigating the impact of multi-species swards on enteric CH$_4$ emissions of beef cattle and lactating dairy cows using the SF$_6$ technique. The current (as of 2021) infrastructure available in Ireland to conduct CH$_4$ research is listed in Table 2.

Discussion

Irish livestock systems are primarily grass-based owing to the temperate climate that promotes grass growth (O'Donovan

| Research centre                        | Facilities                                                                                       |
|----------------------------------------|-------------------------------------------------------------------------------------------------|
| Teagasc Grange                         | 5 × GreenFeed (GF) systems, 4 × Rusitec in vitro simulators, SF$_6$ equipment, digestibility crates for measurements |
| Irish Cattle Breeding Federation Tully | 10 × GF systems (indoor), cattle digestibility units                                               |
| Teagasc Moorepark                      | 4 × GF (pasture), SF$_6$ equipment                                                              |
| Teagasc Athenry                        | Portable accumulation chambers for sheep, SF$_6$ equipment for sheep                             |
| UCD                                    | 4 × GF (pasture/indoor), SF$_6$ equipment, 4 × Rusitec in vitro simulators, digestibility crates for measurements (dairy and sheep) |
| AFBI                                   | 2 × large respiration chambers, 6 × medium respiration chambers, 3 × GF systems, SF$_6$ equipment, dairy cow digestibility units, digestibility crates for measurements |
| Queens University Belfast              | Rumen microbiology laboratory facilities                                                        |
There are also lower economic and environmental costs associated with grass-based systems relative to confinement/feedlot systems (O’Brien et al., 2012; O’Brien et al., 2014; Herron et al., 2021). Thus, investigating how different sward compositions impact CH₄ emissions/emissions intensity from grazing livestock is certainly an avenue worth further investigation. Some research has shown that multi-species swards can decrease daily CH₄ emissions/head and/or directly lower CH₄ emissions intensity through the improved animal performance achieved with grazing multi-species swards (e.g. Hammond et al., 2014). Although, some research does not support these findings, e.g. the study of Loza et al., 2021. Nonetheless, legume-based and multi-species swards require less N fertiliser inputs to maintain yield production and have lower associated N₂O emissions and emissions intensity than conventional L. perenne monocultures (Cummins et al., 2021). Thus, there is the potential that more diverse swards could give dual GHG abatement. Anti-methanogenic feed additives could potentially have a role in Irish CH₄ abatement strategies. However, issues with social acceptance (Beauchemin et al., 2020), cost and on-farm delivery should be taken into account. Due to the constant turnover of the ruminal contents (van Soest, 2018), the efficacy of additives may depend on their residency time in the rumen/frequency of intake. It is easier to deliver additives as part of a TMR diet in housed systems where additives can be supplemented at feeding. This is harder to achieve at pasture level where grazed forage makes up the majority of the animals’ diet. To overcome this, early-life supplementation strategies with additives such as 3-NOP may offer an effective

### Table 3: A summary of current research projects in Ireland that focus on enteric methane

| Project title       | Coordinator          | Funder                  | Duration | Collaborators                                                                                                                                 |
|---------------------|----------------------|-------------------------|----------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Rumenpredict        | Prof Sharon Huws     | ERA-GAS                 | 3 yrs    | QUB, Teagasc, ICBF, UCD, Natural Resources Institute Finland, Agresearch NZ, Swedish University of Agricultural Sciences, Wageningen University, INRA, France |
| MASTER              | Prof Paul Cotter     | EU Horizon 2020          | 4 yrs    | Teagasc, ICBF, Teagasc, IT Sligo, QUB, AFBI, Norwegian Institute of Bioeconomy Research, Agriculture and Agri-Food Canada, Department of Agricultural Sciences Sweden, Friedrich-Loeffler-Institut Germany, SINTEF Norway |
| Seasolutions        | Dr Maria Hayes       | ERA-GAS                 | 3 yrs    | Teagasc, IT Sligo, QUB, AFBI, Norwegian Institute of Bioeconomy Research, Agriculture and Agri-Food Canada, Department of Agricultural Sciences Sweden, Friedrich-Loeffler-Institut Germany, SINTEF Norway |
| Methlab             | Prof Catherine Stanton | ERA-gas               | 3 yrs    | Teagasc, UCC, Wageningen University, INRA, France, Agresearch NZ, SACCO Italy                                                                 |
| Meth-Abate          | Prof Sinead Waters   | DAFM/DAERA              | 4 yrs    | Teagasc, NUIG, AFBI, Queens, Industry                                                                                                        |
| Greenbreed          | Prof Donagh Berry    | DAFM                    | 4 yrs    | Teagasc, ICBF, UCD, WIT, CIT                                                                                                                |
| Grasstogas          | Joanne Conington     | ERA-GAS                 | 3 yrs    | Sheep Ireland, Teagasc, INRA France, National Agriculture Research Institute Uruguay, Norwegian University of Life Sciences, AgResearch NZ, International Center for Livestock Research and Training Turkey |
| Greengrowth         | Dr Fiona McGovern    | Teagasc                 | 4 yrs    | Teagasc, UCD                                                                                                                               |
| SMARTSWARD          | Prof Tommy Boland    | DAFM/DAERA              | 4 yrs    | UCD, Technological University of Dublin, AFBI                                                                                               |
| VistaMilk SFI Research Centre | Prof Donagh Berry | Science Foundation Ireland (SFI) and DAFM, national and international industry funding | Ongoing | Teagasc, UCC, UCD, WIT, multiple national and international industry collaborators                                                        |
| Water-based delivery of rumen modifiers to enhance the sustainability of ruminant production systems | Prof Tommy Boland | Enterprise Ireland | 2 yrs    | UCD                                                                                                                                         |
solution as recently established by Meale et al. (2021). The technological development of slow-release boluses could also provide an option for pasture-based delivery as is often the case with mineral supplementations (Grace & Knowles, 2012; Aliarabi et al., 2019). The effects of additives on animal productivity and welfare will need to be evaluated alongside farm-level cost-effectiveness (i.e. life cycle assessments) to determine the most effective and practical mitigation strategy at farm level.

Selecting for low CH₄ emissions in livestock breeding programmes, that is, including animal CH₄ output in breeding indexes, is a cumulative, permanent and effective CH₄ abatement strategy (González-Recio et al., 2020). In addition, some authors have advocated the benefits of selecting more feed-efficient ruminants as a mitigation strategy (Basarab et al., 2013). Residual CH₄ output is a useful phenotype for use in selection processes, as it is strongly related to daily CH₄ output but also independent of body weight and feed intake (Bird-Gardiner et al., 2017). The work, currently ongoing with Teagasc and the ICBF, will contribute to the development of breeding values for low CH₄ output for both beef and dairy sires as presented in Smith et al. (2021). The benefits of selecting for lower CH₄ output animals would be further complemented with CH₄-inhibiting additives and grazing on multi-species swards. However, breeding indexes will require validation at pasture as there is the possibility of a genetic × feed type effect. Therefore, it is vital that further resources are allocated to continuing and expanding on this research.

A major increase in CH₄ research capacity and output is required. For example, between 2016 and 2021, only 14% of agricultural GHG research publications in Ireland were focused on enteric CH₄ (Figure 1). Therefore, research outputs seem to be disjointed from research requirements given that enteric CH₄ emissions from livestock production constitute 57% of Irish agricultural GHG emissions. Thus, considerable investment towards research infrastructure and facilities is urgently required if the Irish CH₄ research capacity is to expand and progress. Regarding specific infrastructures (Table 2), there are currently no RCs in use in the Republic of Ireland. These will be required as RCs are a fundamentally important methodology for measuring CH₄ emissions and for validating other CH₄ measurement methodologies. More individual feeding and feed intake recording systems would be useful to assess further the relationship between genotype, feed use efficiency and CH₄ emissions from a large cohort of animals for breeding purposes. There is also a need for more accurate methodologies for measuring feed intake from grazing animals and further investment in pasture-based GF systems for large-scale field trials. Additionally, there is a need to investigate and further develop upcoming technologies for measuring CH₄ emissions (Neethirajan, 2020) for application to grazing systems. Research would ideally take place at a multi-institutional level and capture CH₄ emissions from dairy, beef and sheep production systems (both intensive and extensive) across Ireland.
In order to improve and refine the national enteric CH₄ inventory, the working data (i.e. yearly livestock numbers from the CSO) should be combined with existing research output to develop a dynamic CH₄ model for inclusion within the national inventory. This would ideally be performed for sheep, beef and dairy cattle aiming to progress sheep inventory from Tier 1 to Tier 2 (with the aim of further progression to Tier 3) and cattle from Tier 2 to Tier 3. Further emission factor and inventory development will provide increased accuracy in Ireland’s GHG emissions estimations and therefore mitigation efforts. An accurate inventory accounting is essential for determining the efficacy of mitigation efforts and meeting carbon neutrality in Ireland by 2050.

Thus in summary, research is required in the following areas: (1) on-pasture deliverance of anti-methanogenic substances in the form of additives, for example, 3-NOP, oilseeds, seaweeds; (2) the effects of sward type on CH₄ emissions and emissions intensity at pasture level including the effects of different species; and (3) breeding efficiency: selecting for low CH₄-emitting genetics while retaining production and profitability. The capabilities and limitations of all mitigation options should be considered during the development of a national CH₄ abatement strategy and a holistic approach should be taken rather than a “silver bullet” solution. The meeting of GHG commitments will be dependent on policy drivers and technology adaptation. Knowledge transfer and advisory will also have key roles with the on-farm delivery of abatement strategies.

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