Cleaner Environmental Systems

Life Cycle Assessment of a Hydrogen Peroxide-Based Slurry Amendment in an Irish Dairy System

--Manuscript Draft--

Manuscript Number:	
Full Title:	Life Cycle Assessment of a Hydrogen Peroxide-Based Slurry Amendment in an Irish Dairy System
Short Title:	
Article Type:	Full Length Article
Keywords:	Life Cycle Assessment; Slurry Chemical Amendment; Greenhouse Gases; Decarbonisation
Corresponding Author:	Luis Alejandro Vergara University College Dublin IRELAND
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University College Dublin
Corresponding Author's Secondary Institution:	
First Author:	Luis Alejandro Vergara
First Author Secondary Information:	
Order of Authors:	Luis Alejandro Vergara
	Joseph Sweeney
	Fionnuala Murphy
	Dermot Hughes
	Stephen Nolan
Order of Authors Secondary Information:	
Abstract:	This study evaluates the environmental impact of a chemical slurry amendment applied on a commercial Irish dairy farm using a LCA framework. A hydrogen peroxide-based additive was tested in a controlled slurry storage trial, achieving an 80% reduction in CH_4 emissions and near-total abatement of NH_3 volatilisation over an eight-week period. These emission factors were scaled to represent farm-level conditions at Shinagh Farm and compared to both a baseline system and a representative conventional farm. The results show that implementing the additive reduced CH_4 emissions from slurry storage by 67–79%, lowered the whole-farm carbon footprint by 2–3%, and decreased ammonia-related acidification potential by up to 3.2%. The mitigation effect was more pronounced in the conventional farm scenario, where manure management emissions were higher. Sensitivity analysis confirmed the robustness of results, while highlighting the importance of emission factor selection and farm-specific parameters. The findings demonstrate the additive's potential to significantly reduce gaseous emissions from manure storage without pollution swapping. Although its overall effect on total farm emissions is modest, the strategy offers a targeted and scalable approach to support compliance with climate and air quality goals in Irish pasture-based dairy systems.
Opposed Reviewers:	
Additional Information:	
Question	**Response**

To complete your submission you must select a statement which best reflects the availability of your research data/code. IMPORTANT: this statement will be published alongside your article. If you have selected "Other", the explanation text will be published verbatim in your article (online and in the PDF). (If you have not shared data/code and wish to do so, you can still return to Attach Files. Sharing or referencing research data and code helps other researchers to evaluate your findings, and increases trust in your article. Find a list of supported data repositories in Author Resources, including the free-to-use multidisciplinary open Mendeley Data Repository.)	Data will be made available on request.
Once your paper is submitted you will be unable to make any further changes to the authorship. Please take a moment to ensure that all the authors who worked on this paper are correctly listed. Any requests for authorship changes further down the line will result in rejection and ONLY in specific cases and after agreement of the Handling Editor and the Editor-in-Chief, you can resubmit your paper as a new submission. Articles with affiliations from more than three different countries will need to provide the editors with a separate letter explaining how the collaborations came about, the contributions of these of each of the participating research teams, and details on how the collaborations were coordinated.	I hereby acknowledge that I have read, understand, and agree to these policies

Declaration of Interest

I, Luis Alejandro Vergara, declare that I have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this chapter.

The hydrogen peroxide-based slurry amendment examined in this study was tested in collaboration with the Farm Zero C project at Shinagh Farm. The experimental additive was supplied by GlasPort Bio for trial purposes only. Neither I nor my affiliated institutions have any commercial stake in the proprietary product evaluated. Data interpretation and life cycle assessment modelling were conducted independently by the research team.

Chapter 5 Life Cycle Assessment of a Hydrogen Peroxide-Based Slurry Amendment in an Irish Dairy System

1.1 Abstract

This study evaluates the environmental impact of a chemical slurry amendment applied on a commercial Irish dairy farm using a LCA framework. A hydrogen peroxide-based additive was tested in a controlled slurry storage trial, achieving an 80% reduction in CH_4 emissions and near-total abatement of NH_3 volatilisation over an eight-week period. These emission factors were scaled to represent farm-level conditions at Shinagh Farm and compared to both a baseline system and a representative conventional farm.

The results show that implementing the additive reduced CH_4 emissions from slurry storage by 67–79%, lowered the whole-farm carbon footprint by 2–3%, and decreased ammonia-related acidification potential by up to 3.2%. The mitigation effect was more pronounced in the conventional farm scenario, where manure management emissions were higher. Sensitivity analysis confirmed the robustness of results, while highlighting the importance of emission factor selection and farm-specific parameters.

The findings demonstrate the additive's potential to significantly reduce gaseous emissions from manure storage without pollution swapping. Although its overall effect on total farm emissions is modest, the strategy offers a targeted and scalable approach to support compliance with climate and air quality goals in Irish pasture-based dairy systems.

1.2 Introduction

Manure management in Ireland's rapidly expanding dairy sector has become an acute environmental challenge. Cattle slurry is a significant source of CH_4 and NH_3 emissions, contributing approximately 9% of global agricultural CH_4 and 17% of NH_3 emissions (FAO, 2023; UNECE, 2021). In Ireland, agriculture is responsible for over 99% of national NH_3 emissions and about 38% of national GHG emissions (EPA, 2023). CH_4 from stored slurry is a potent GHG with a GWP_{100} of around 27 (IPCC, 2021), while NH_3 volatilization from slurry leads to nitrogen loss, fine particulate matter formation, and ecosystem nitrogen deposition. Conventional slurry management practices (as examined in Chapter 4) can therefore significantly influence a dairy farm's carbon and NH_3 footprints. For example, in a baseline scenario at the case study farm, untreated slurry storage and land spreading emitted substantial CH_4, contributing approximately 0.07 kg CO_2-eq per kg FPCM (roughly 10% of the farm's GHG intensity of ~0.67 kg CO_2-eq per kg milk) – and were the dominant source of NH_3, accounting for the vast majority (on the order of 90%) of the farm's NH_3 emissions. This amounted to 2,794 kg NH_3 annually, or 2.11 g NH_3 per kg FPCM. Although this is below the national average of 5.09 g NH_3/kg FPCM (Buckley and Donnellan, 2020), the cumulative impact across the dairy sector is substantial. Applying the national average to Ireland's 2022 milk output (approximately 9.1 billion kg FPCM), dairy alone is estimated to have emitted approximately 46.4 kt of NH_3, representing around 40% of the national ceiling of 116 kt under the EU National Emissions Ceilings Directive (EPA, 2023). This leaves limited remaining headroom for emissions from other livestock sectors such as beef and swine, which also rely heavily on slurry-based systems. As such, even relatively efficient dairy farms will face increasing pressure to reduce emissions further. The need for more advanced manure management strategies, such as slurry acidification, low-emission spreading, or chemical amendments, is therefore critical to achieving compliance with both climate and air quality targets, including Ireland's legally binding commitment to reduce agricultural GHGs by 25% by 2030 (Government of Ireland, 2022).

Multiple mitigation approaches have been explored to curb emissions from stored slurry and land application. Covering slurry stores – using fixed lids or floating covers – can greatly reduce NH_3 losses (studies report reductions of 40–80%) by physically blocking NH_3 volatilization, and under optimal conditions can also reduce CH_4 emissions by capturing biogas (Misselbrook et al., 2016; Kupper et al., 2020). However, the effectiveness of covers on CH_4 is variable (permeable covers often have limited impact on CH_4 unless the gas is collected and flared), and installing covers entails significant cost and management changes. Another well-established strategy is slurry acidification, where acids (typically sulfuric acid) are added to lower the slurry pH. Lowering pH shifts the ammonium–NH_3 equilibrium toward the non-volatile ammonium form, thereby cutting NH_3 emissions by 50–80%, and simultaneously inhibits the microbial methanogenesis process, yielding substantial reductions in CH_4 production (Misselbrook et al., 2016; Hou et al., 2014; Sokolov et al., 2021; Overmeyer et al., 2023). While highly effective, acidification requires handling of corrosive substances and can alter slurry nutrient composition (e.g. increasing available nitrogen and sulfur), which raises practical and safety considerations. At the land-spreading stage, using low-emission slurry spreading (LESS) techniques such as trailing hoses or injection can further abate NH_3 losses – often by 30–60% compared to splash-plate spreading – by delivering slurry directly to the soil and reducing surface exposure (Amon et al., 2006). Indeed, LESS was implemented at the case study farm (Chapter 4) as part of conventional best practices. However, such application-stage measures do not address the CH_4 released during storage, which can account for 15–30% of total manure-related GHG emissions on dairy farms. Even when slurry is stored under floating or impermeable covers, residual CH_4 emissions often persist at rates of 1.0–2.5 g CH_4 per kg of volatile solids, depending on temperature, storage duration, and cover effectiveness (Petersen et al., 2013; Montes et al., 2013). Other methods to mitigate slurry emissions include aeration or frequent slurry stirring to increase oxygen exposure (which can suppress CH_4 generation but are energy-intensive) and various slurry additives. For instance, adding nitrates to slurry can provide an alternative electron acceptor for microbes, thereby curbing methanogenesis – but this may lead to by-products like N_2O and has seen limited on-farm use. Similarly, amendments like alum or other salts have been tested to bind ammonium and reduce NH_3 volatilization, yet their effects on CH_4 are minimal and results have been mixed (Owusu-Twum et al., 2025; Lefcourt et al., 2001; Regueiro et al., 2016). In practice, each of these measures tends to target one pollutant more than the other or introduces new costs and complexities. Few interventions can simultaneously cut both CH_4 and NH_3 emissions without significant trade-offs, underscoring the need for novel solutions.

One emerging approach to tackle both gases is the use of oxidizing agents as slurry amendments. By chemically oxidizing the slurry environment, these additives aim to inhibit anaerobic decomposition (thereby suppressing CH_4 production) and stabilize nitrogen in less volatile forms (thereby reducing NH_3 loss). Recent studies provide proof-of-concept for this strategy. Nolan et al. (2023) demonstrates that adding a peroxide-based additive to pig slurry reduced overall gaseous emissions by over 60%, including roughly a 50% decrease in NH_3 volatilization and a marked reduction in CH_4 output. These findings align with the efficacy observed for slurry acidification and highlight that chemical amendments can effectively target both major emissions from manure. An oxidizing treatment such as H_2O_2 offers a different mechanism from acidification: rather than lowering pH, H_2O_2 releases oxygen and reactive radicals into the slurry, directly oxidizing organic substrates and ammonium. This process can elevate the redox potential of the slurry, inhibiting the strictly anaerobic methanogenic archaea and potentially converting some ammonium NH_4 to nitrate NO_3 or other oxidized forms, thus retaining nitrogen in the manure while preventing its volatilization as NH_3. The use of H_2O_2 as a manure additive is novel in the context of dairy farming and offers certain operational advantages over acidification techniques, such as avoiding permanent infrastructure like tank covers or slurry injection systems. While concentrated H_2O_2 (>30%) is highly corrosive and poses severe health risks (e.g. chemical burns, eye damage), the concentration trialled in this study was a 5% diluted solution, classified as irritant but not corrosive under EU Classification, Labelling and Packaging (CLP) regulations (ECHA, 2023). This significantly reduces handling risks relative to acid-based additives such as sulphuric acid, although standard PPE and controlled application protocols remain essential.

Technology	CH_4 Emission Impact	NH_3 Emission Impact	Mechanism of Action	Key Challenges / Limitations
Floating or fixed covers	↓ Variable (10–90%)	↓ 40–80%	Physical barrier to gas release from slurry surface	Costly; fixed infrastructure required; less effective for CH_4 without flaring
Slurry acidification	↓ ~60–70%	↓ 50–80%	pH reduction stabilizes NH_4^+; suppresses methanogens	Requires acid handling; corrosive risk; infrastructure adaptation needed
Low-emission slurry spreading (LESS)	↔ / N/A	↓ 30–60%	Places slurry close to soil to reduce NH_3 volatilization	Does not address storage-phase CH_4; equipment cost
Aeration / frequent stirring	↓ ~30–50%	↔ / variable	Increases oxygen diffusion, inhibits anaerobic decomposition	High energy demand; operational burden; possible NH_3 increases
Alum / salts (e.g., $Al_2(SO_4)_3$)	↔ / uncertain	↓ Moderate (30–50%)	Binds ammonium and reduces NH_3 volatilization	Variable effectiveness; can alter slurry pH and nutrient value
Nitrate or sulfate additives	↓ 30–70%	↔ / may increase	Alternative electron acceptors disrupt methanogenesis	Risk of N_2O formation; limited field testing

H_2O_2 amendment (this study)	↓ ~80% (trial result)	↓ ~100% (NH_3 eliminated)	Oxidation raises redox potential; stabilizes nitrogen; suppresses CH_4	Requires careful dosing and handling; corrosive at high concentrations; novel technology still under evaluation

Table 5.1: Summary of slurry emission mitigation technologies

This chapter builds on the above developments by evaluating the use of H_2O_2 as a slurry amendment in a real-world dairy farm setting. The core research question addressed is whether treating stored slurry with H_2O_2 can substantially mitigate CH_4 and NH_3 emissions at the farm scale and, if so, what net effect this has on the farm's overall environmental impacts relative to conventional slurry management. To answer this, we integrate empirical data from an on-farm slurry amendment trial (conducted at Shinagh Farm in 2022) with a LCA model. A cradle-to-farm-gate LCA approach – consistent with the framework established in Chapter 4 – is employed to rigorously quantify the environmental impacts of implementing the H_2O_2 treatment. The analysis follows the ISO 14040/14044 standards for LCA (ISO, 2006) and uses the same functional unit of 1 kg of FPCM. The system boundary mirrors that of the conventional scenario (Chapter 4), encompassing all relevant stages from upstream resource production (e.g. manufacturing and transport of inputs like fertiliser, feed, and the H_2O_2 additive) to on-farm processes (including animal management, manure storage, and field application of slurry). All life cycle processes associated with the H_2O_2 treatment – production, transportation, storage, and application of the H_2O_2 – are included in the model alongside the baseline farm operations. This ensures that any upstream burdens of the chemical amendment (such as CO_2 emissions from H_2O_2 manufacture or fuel use for its transport) are accounted for and weighed against the on-farm emission reductions it achieves. Emission factors and impact assessment methods are updated to reflect the latest science and maintain methodological rigor. Notably, GHG emissions are characterized using 100-year GWP_{100} from the IPCC Sixth Assessment Report (i.e. AR6 GWP_{100} values for CH_4, N_2O, etc., IPCC, 2021) to capture the most up-to-date estimation of CH_4's climate impact. Environmental impacts such as AP and EP are evaluated using the CML-IA baseline methodology (Guinée et al., 2002), in line with prevailing LCA practice. By maintaining consistency in scope and indicators with the previous chapter's LCA of the conventional system, the effects of the H_2O_2 intervention on key outcomes – GHG emissions, NH_3 losses, and other impact categories – can be isolated and directly compared to the untreated baseline.

This study is among the first to apply a full life-cycle perspective to a H_2O_2-based slurry treatment in a working farm context. By combining empirical trial data with an ALCA, the analysis provides a robust, holistic assessment of both the direct mitigation potential of the H_2O_2 amendment and any indirect environmental trade-offs. In doing so, it offers novel insights into the viability of using an oxidative slurry amendment to simultaneously address CH_4 and NH_3 emissions – a contrast to more conventional mitigation measures (e.g. acidification, storage covers, or LESS) that may target one impact more than the other. Importantly, the life-cycle approach ensures that the benefits of the H_2O_2 treatment (such as reduced on-farm emissions and enhanced fertiliser value of the slurry due to higher nitrogen retention) are evaluated against the costs (e.g. the emissions and resources required to produce and apply H_2O_2). The outcome of this assessment will indicate whether, on balance, the H_2O_2 amendment yields a net environmental advantage for the dairy system.

1.3 Materials and Methods

1.3.1 Goal and Scope

The goal of this study is to evaluate the cradle-to-farm-gate environmental impacts of milk production at a commercial dairy farm in Ireland (Shinagh Farm, Co. Cork) for the year 2022, and to assess the effect of a novel manure management practice, a slurry additive, on those impacts. A comparative LCA approach is used to examine two scenarios: (i) the Shinagh Farm system in 2022, where the slurry additive was applied under trial conditions alongside otherwise standard best practices, and (ii) a representative conventional Irish dairy farm system without the additive, reflecting typical regional management. By comparing these two systems under consistent assumptions, the analysis isolates the potential benefits of the slurry amendment in an Irish dairy context.

An ALCA framework is applied, allocating all direct environmental burdens to the functional unit without modeling broader market-induced effects. This approach is appropriate for farm-scale comparisons of management practices. The system boundary is defined as cradle-to-farm-gate, encompassing all relevant upstream and on-farm processes up to the point where milk leaves the farm. Included are the production and transport of inputs (e.g. fertilisers, feed, fuel, electricity), on-farm enteric fermentation, manure handling (storage and land application), animal housing and milking operations, and internal nutrient cycling via manure. Co-products such as livestock sales (culled cows, surplus calves) and the use of manure as fertiliser are accounted for within the boundary. Processes beyond the farm gate – milk hauling, processing, packaging, distribution, and consumption – are excluded from this study's scope.

The analysis focuses on steady-state farm operation in 2022; capital infrastructure and one-time land use change are not considered, as no land conversion occurred during the assessment year. Manure is treated as an internal flow: emissions from slurry storage and spreading are fully attributed to the farm, while nutrients returned to soil via slurry are credited for offsetting a portion of synthetic fertiliser requirements. All on-farm land use for feed production (pasture, silage) is included, with no land use change assumed in the reference year. The study follows the ISO 14044 methodology (ISO, 2006) for goal definition, scope setting, life cycle inventory compilation, and impact assessment. Consistent system boundaries and functional units are maintained across both scenarios to enable a transparent, like-for-like comparison of the two manure management strategies in an Irish dairy system.

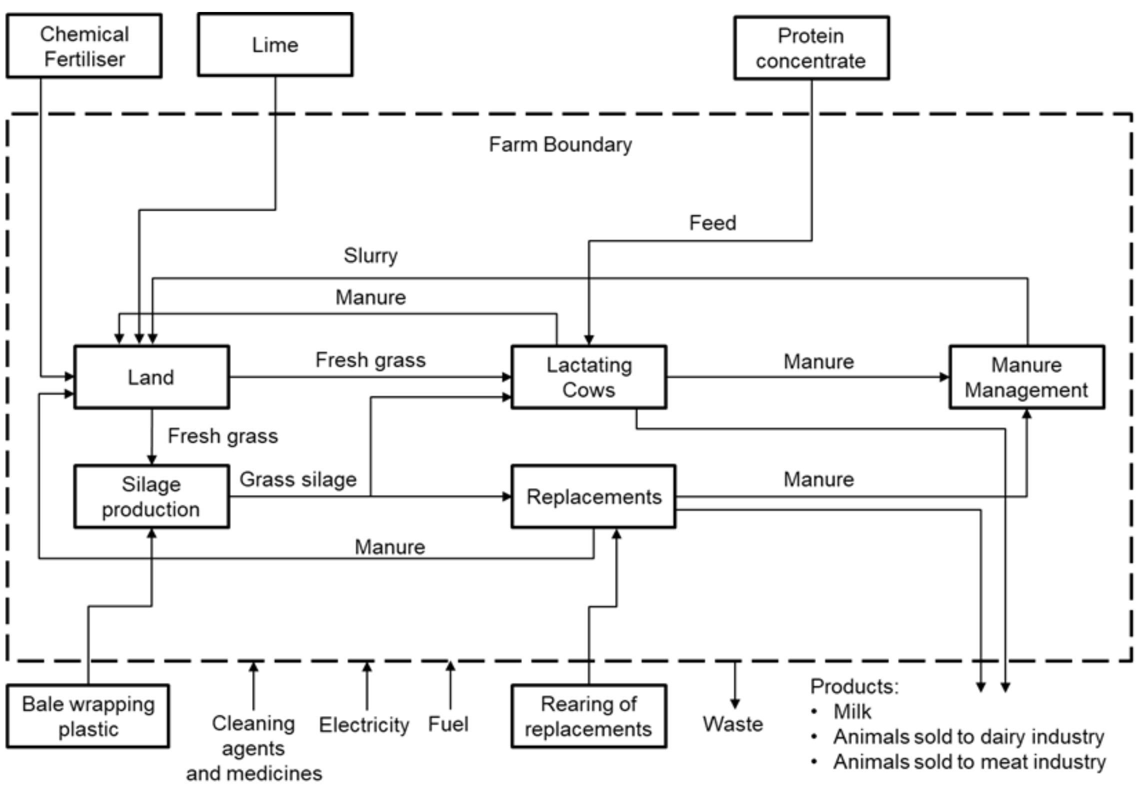

Figure 5.1: Slurry Chemical Amendment - LCA System Boundary

The functional unit is defined as 1 kg of FPCM at the farm gate. Using FPCM as the functional unit standardises milk outputs between farms by adjusting for milk composition (energy and protein content), ensuring results are comparable. All resource inputs and emissions are quantified per this unit of milk. In the Shinagh system, milk is the primary output but beef is co-produced from culled animals and surplus calves; therefore, a partitioning of impacts between milk and meat is necessary. A biophysical allocation approach is employed following established guidelines (IDF, 2015; Teagasc, 2022), which allocates environmental burdens in proportion to the energy and protein requirements for milk production versus live-weight gain. This method reflects the biological resource use of the herd and assigns the vast majority of the impacts to milk, with only a small share allocated to meat. By using this allocation (approximately >90% of impacts to milk), the functional unit impact is focused on milk production, aligning with dairy industry standards.

1.3.2 Life Cycle Inventory

A detailed life cycle inventory (LCI) was assembled for both the Shinagh Farm case and the conventional farm reference, capturing all inputs, outputs, and emissions for the 2022 production year. For Shinagh Farm, primary data were collected from farm records and on-site measurements. These included herd metrics (a milking herd of 247 cows in 2022, with replacement heifers reared on-farm), milk production (total ~1.325 million kg FPCM in 2022), and management details such as grazing and housing durations, feeding regimes, manure handling practices, and resource use. Manure from the cow herd was stored in covered slurry pits for approximately three months during the winter housing period, while manure from replacement stock was managed through a combination of solid manure and partially covered tanks, in line with typical practice (see Table 5.1). Key information was obtained from milk yield records, input purchase logs (e.g. concentrates, fertiliser, diesel), and farm management diaries (e.g. number of grazing days (~251 days fully at pasture in 2022), housing period lengths (~76 days housed for lactating cows), and use of low-emission spreading equipment). These site-specific data provide an accurate account of Shinagh's management in the study year. In contrast, the conventional farm was defined using aggregated national farm statistics, principally the Teagasc National Farm Survey for dairy farms (Buckley and Donnellan, 2023). This representative conventional farm is a mid-sized Irish dairy enterprise in 2022 with about 90–100 cows (≈93 cows assumed) and more typical practices: a shorter grazing season (~225 days) with a longer winter housing period. Manure from cows is assumed to be stored in uncovered external tanks for five to six months, with heifer and calf manure handled via uncovered tanks or solid storage. Slurry is land-applied using predominantly splash-plate methods. Input levels for fertiliser and feed reflect national averages. Table 5.1 provides a side-by-side overview of the key herd and management parameters for Shinagh versus the conventional farm. Notable differences include Shinagh's larger herd and land base (101 ha vs 66 ha), higher overall productivity, and its implementation of certain mitigation practices (for example, Shinagh employs trailing-shoe slurry spreading for 100% of slurry, whereas the conventional farm relies roughly 50% on splash-plate spreading). These differences in the inventory are expected to influence the environmental outputs and are important for interpreting the results of the comparison.

Parameter	Shinagh Farm 2022	Conventional Farm	Unit
Farm size	101	66	Hectare
Eircode	P72X050	-	-
Number of cows	247	93	Livestock Units
Replacement rate	18	22	%
Average lactating days	288	257	Days
Milking frequency	2	2	Times/day
Breeding system	Sexed semen	Sexed semen	Type
Days cows fully grazing	251	225	Days
Days cows partially grazing	38	32	Days
Days cows are housed	76	108	Days
Housing days for heifers	120	145	Days
Housing days for calves	141	179	Days
Manure management type	Cows: Covered pit storage for 3 months. Heifers: Covered pit storage for 3 months. Calves: Solid manure storage.	Cows: Uncovered external tank storage for 6 months. Heifers: Covered tank outside housing for 4 months. Calves: Solid manure storage.	Type
Slurry spreading method	Trailing Shoe	Splash Plate (52%), Trailing Shoe (48%)	Type
% slurry spread on fields	100% cows; 0% heifers/calves	100% all	%
Electricity demand (grid)	33,862	36,560	kWh
Diesel demand	3,000	2,800	L
Kerosene demand	1,000	0	L

Lime usage	20,360	20,360	Kg
Animal sales outside dairy	44,676	9,768	Kg
Fertiliser usage	Protected Urea 46-0-0: 16.5; GEN 29-0-14: 23.6; 10-10-20: 4.5; 0-7-30: 16.3	Urea 46-0-0: 5.7; CAN 27-0-0: 27.5; Protected Urea 46-0-0: 3.0	Ton
Concentrate usage cows	Irish Blend: 238.2	Coarse Dairy 16%: 99.7; Dairy Cubes 16%: 25.2; Coarse Summer 16%: 11.7	Ton
Concentrate usage calves	Calf Starter: 4.9	Calf Starter: 5.0	Ton
Milk production	1,325,004.1	567,649.9	Kg FPCM
Type of drainage	Well drained	Average	-

Table 5.1: Shinagh Farm 2022 and Conventional Farm - Life Cycle Inventory

Given that manure management is central to this study, the LCI explicitly quantifies manure and nutrient flows for both systems. For the conventional farm, manure production was estimated using standard per-animal excretion rates and housing durations derived from national data, assuming typical storage and spreading methods as noted (e.g. slurry stored ~6 months over winter in a tank for the cows, with younger stock managed similarly or in solid manure as appropriate). For Shinagh Farm, a more detailed mass-balance approach was used to model manure and nutrient flows, following IPCC Tier 2 methodology (IPCC, 2019). Herd feed intake and milk output data were used to estimate nutrient excretion: nitrogen intake was inferred from the cows' diet (crude protein content of feed) and nitrogen output in milk was subtracted to calculate total nitrogen excreted by the herd. This yielded an estimated total of approximately 3.39×10^3 kg of nitrogen excreted by the lactating cows at Shinagh in 2022. Using typical nitrogen concentrations in dairy slurry (on the order of 3.5–4.5 kg N per m³ of slurry; O'Brien et al., 2014; Teagasc, 2019), the corresponding slurry volume for Shinagh's milking cows was about 885 m³ for the year. This estimate aligns closely with an independent calculation based on the housing period for lactating cows (76 days) and typical slurry output rates of approximately 0.33 m³ per cow per week, which equates to roughly 3.6 m³ per cow over the housing period, lending confidence to its accuracy.

Table 5.2 summarises the annual manure quantities and storage parameters for Shinagh Farm and the conventional farm, and also places these in context of the experimental IBC (Intermediate Bulk Container) scale described below. In total, Shinagh Farm produces on the order of ~970 m³ of slurry per year that comprises of 885 m^3 from dairy cows and 85 m^3 from heifers and calves, whereas the smaller conventional farm produces around ~525 m^3 per year. The dry matter content of fresh slurry is assumed to be approximately 8–10% in both systems, consistent with values measured at Shinagh (the initial slurry in the Shinagh trial was ~9% dry matter) and literature values for Irish dairy slurry. At Shinagh, slurry from the cow herd is stored in covered below-ground pits for approximately three months, whereas in the conventional scenario, cow slurry is assumed to be stored in uncovered external tanks for five to six months over winter. Heifer and calf manure are managed using either covered storage or solid systems, in line with typical practice (see Table 5.1). All stored manure is eventually land-applied as organic fertiliser on grassland: Shinagh uses only trailing hoses (trailing shoe) for slurry spreading, whereas the conventional farm uses a mix of splash-plate and trailing shoe methods (about half of slurry spread via each, reflecting average adoption rates). Manure nitrogen returned directly to pasture by grazing animals (excreted on fields during grazing days) is accounted for separately in the LCI as a direct soil input; those N flows bypass storage but are included in overall emissions through field emission factors. In summary, the inventory accounts for the full manure nitrogen cycle in each system, either through the slurry management pathway or via direct deposition on land, to ensure all emissions related to manure are captured.

Parameter	Shinagh Farm 2022	Conventional Farm	IBC Trial (per container)
Dairy cows (count)	247	93	–
Housing period (cows)	76 days	108 days	~56 days (8 weeks)
Slurry produced per cow	≈3.6 m^3 over 76 d	≈5.1 m^3 over 108 d	–
Total slurry volume (cows)	~885 m^3/year	~475 m^3/year	1 m^3
Additional slurry from replacements	~85 m^3/year	~50 m^3/year	–
Total slurry managed	~970 m^3/year	~525 m^3/year	1 m^3
Typical slurry dry matter	~8–10% DM (fresh basis)	~8–10% DM (fresh basis)	~9% DM (initial)
IBC volume as % of farm total	0.10% (1 m^3 of 970)	0.19% (1 m^3 of 525)	–

Table 5.2: Annual manure production and storage volumes for Shinagh Farm and a conventional Irish dairy farm, and comparison with IBC trial scale

To model the impact of the slurry amendment at the farm scale, primary experimental data were incorporated from an on-farm slurry storage trial conducted at Shinagh in 2022. The trial was designed and implemented by the Farm Zero C project team (not by the author), with data made available through collaboration with GlasPort Bio and project partners. In this controlled experiment, Shinagh Farm tested the additive's effect using six Intermediate Bulk Containers (IBCs), each of ~1 m^3 capacity, filled with fresh cattle slurry collected from the dairy housing facility (representative of the farm's winter slurry). Three IBCs served as untreated control vessels, while the other three were treated with a proprietary slurry additive supplied by GlasPort Bio that releases oxidizing agents (principally hydrogen peroxide, H_2O_2) intended to suppress greenhouse gas and ammonia emissions. The IBCs were kept in winter-like conditions for an 8-week period (~56 days) to simulate typical slurry storage duration on the farm. Throughout this trial, biogas production and composition were monitored regularly for each container: cumulative gas volume was measured and gas samples were analyzed to determine CH_4, CO_2, NH_3, H_2S, and O_2 concentrations. In parallel, slurry samples were taken from each IBC every two weeks and analysed for key chemical properties, including ammoniacal nitrogen (NH_4-N), total nitrogen, dry matter content, pH, and concentrations of nutrients such as phosphorus (P), potassium (K), and sulfur (S). While the IBCs provide a controlled and repeatable experimental platform, they are a simplified proxy and do not replicate all physical and environmental characteristics of the full-scale, below-ground concrete pits used at Shinagh. A critical discussion of these differences and the implications for scaling the results is provided in the following section (see Subsection 5.4.2.1: Storage System Comparability).

The IBC trial revealed that the oxidizing additive substantially reduced both CH_4 and NH_3 emissions during storage. In the treated containers, total biogas generation was lower than in the controls, and critically the biogas from treated slurry had a much lower CH_4 fraction. Consequently, the cumulative CH_4 emitted over the 8 weeks was significantly lower for treated slurry compared to untreated slurry. Moreover, NH_3 volatilization was virtually eliminated in the treated IBCs – essentially a 100% reduction in ammonia release relative to the controls over the trial period. These measured outcomes were used to calibrate the manure emission factors in the LCA. In practice, the emission rates observed at IBC scale were applied to the farm's total slurry volume to estimate annual emissions with and without the additive.

Aside from manure management, the LCI integrates all other farm inputs and activities to calculate total environmental flows for each system. This includes feed production and use, fertiliser manufacture and application, fuel and energy consumption, and livestock-related emissions (e.g. enteric methane and direct N_2O from soils). Wherever possible, Ireland-specific emission factors and farming practice data are used to reflect local conditions – for example, emission factors for manure management are tailored to Irish climate and management circumstances, and IPCC (2019) guidance is followed for calculating greenhouse gas emissions from livestock and soils. A complete list of emission factors and parameters used in the model is provided in Appendix Table A3. By using country-specific data and integrating the on-farm trial results, the inventory is able to capture the nuances of an Irish dairy system employing this novel slurry amendment. In summary, the LCI captures all relevant material and energy flows and emissions for both the Shinagh and conventional farms under their respective management regimes. This comprehensive inventory serves as the foundation for the life cycle impact assessment in the next section, wherein the environmental impacts of the baseline and amended scenarios are quantified and compared.

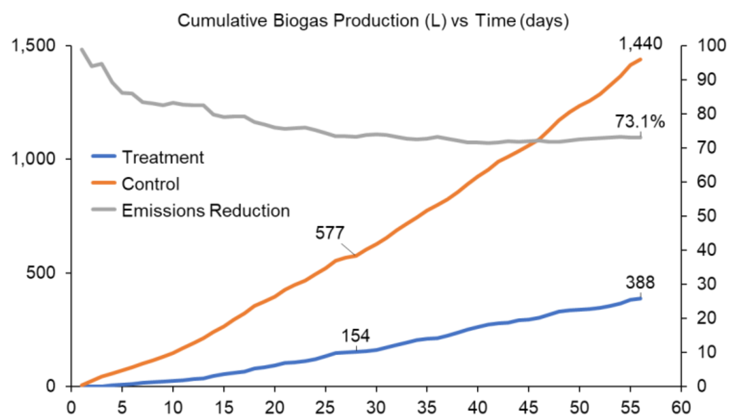

Figure 5.2: Manure Cumulative Biogas Production During Slurry Chemical Amendment Trial

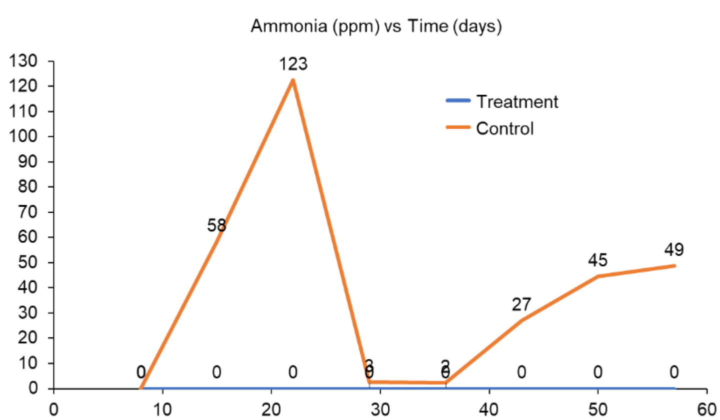

Figure 5.3: NH_3 Emissions During Slurry Chemical Amendment Trial

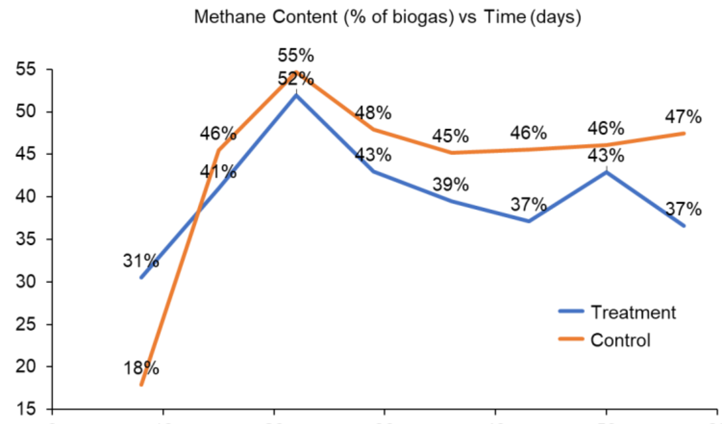

Figure 5.4: CH_4 Content in Biogas During Slurry Chemical Amendment Trial

5.4.2.1 Storage System Comparability

Extrapolating the IBC results to full-scale farm conditions required some assumptions. It was assumed that the percentage reductions in CH_4 and NH_3 observed over the 8-week IBC trial would be maintained over a typical ~12-week winter storage period in a farm slurry tank. This assumption is supported by the observation that in the control IBCs most CH_4 and NH_3 emissions occurred in the first 6–8 weeks, indicating that extending to 12 weeks would not likely produce disproportionately higher emissions beyond what was measured. The slurry used in the IBCs was fresh and representative of Shinagh's actual manure (in terms of dry matter and nutrient content), and the storage conditions (static, unagitated storage with limited exposure to external environment) mimic the covered pit storage at Shinagh reasonably well. Admittedly, full-scale tanks (~300 m^3 capacity) may exhibit additional dynamics – for instance, a larger surface area could allow some crust formation or minor atmospheric interactions, and ambient temperature fluctuations could differ – but in the absence of evidence to the contrary, a like-for-like scaling of emission factors is considered appropriate. In essence, we assume that on a per-cubic-metre basis, the additive would yield similar emission reductions in the farm's slurry pit as observed in the IBCs. This introduces some uncertainty, but it is a necessary step to integrate the experimental findings into the whole-farm model. It is acknowledged this uncertainty and address it through sensitivity analysis (see Chapter 5.5.4) to ensure that the conclusions are robust to reasonable variations in the assumed mitigation efficiency. Ultimately, the LCI applies the empirically derived emission factors from the trial for Shinagh's additive scenario and uses the control (untreated) factors for Shinagh's baseline scenario. By grounding the manure emissions in site-specific measurements (as opposed to solely default factors), the inventory provides a credible and context-specific representation of the slurry additive's mitigation potential. In contrast, the conventional system's manure emissions remain based on generic emission factors, since no additive or novel practice is in place for that scenario.

Day	Day 0						Day 28						Day 56					
Type	Control			Treatment			Control			Treatment			Control			Treatment		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Cumulative Biogas Production (L)	8.82	6.24	7.89	0.66	0	0.24	616.6	557.4	557.7	144.5	139.3	177.8	1568.5	1494.1	1257.9	327.2	345.4	491
Cumulative CH_4 Production (L)	0	0	0	0	0	0	308.6	241.4	281.1	59	60.3	79.8	746.6	706.7	596.3	100.5	139.5	189.5
Cumulative NH_3 Production (ppm)	0.09	0.06	0.08	0	0	0	6,234	7,042	11,186	0	0	0	28,232	103,090	74,217	0	0	0
Manure Total NH_3 cal N (mg/kg)	2273	2631	3165	2080	1833	2324	1843	1932	1818	1907	1870	1899	1872	1959	1702	2039	1908	2072
Manure Dry Matter Content (%)	8.9	8.83	9.26	9.13	8.88	9.07	3.35	6.2	3.21	6.27	21.22	7.98	2.64	3.11	2.94	3.61	3.3	3.52
Manure pH	7	7.1	7.1	7.1	7.1	7	7.2	7.3	7.3	7.5	7.2	7.8	8	8	8.1	8.1	8.1	8.1
Sulphur (units/1000gls)	1.91	1.58	1.56	1.81	1.82	1.8	0.46	0.12	0.38	1.81	0.97	1.2	0.37	0.35	0.26	2.51	0.44	0.42
Phosphorus (units/1000gls)	8.41	9.79	6.81	8.53	8.35	9.82	1.02	2.19	1.08	2.3	2.13	3.2	2.25	2.56	4.01	2.31	1.94	2.5
Potassium (Units/1000gls)	35.89	34.96	35.7	35.93	35.99	35.37	24.3	26.8	30.1	24.2	5.21	31.3	32.16	30.96	45.9	29.27	27.8	31.6
N (units/1000gls)	19.55	20.47	20.49	19.63	19.63	23.67	17.42	20.59	19.41	19.54	19.82	23.36	17.81	18.64	19.18	20.07	19.6	18.86

Table 5.3: Slurry Chemical Amendment Trial Result

1.3.3 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) evaluates the environmental impacts of each farm system based on the compiled inventory data. In this chapter, the primary impact categories of interest are climate change and air quality (specifically ammonia-related) impacts, given the focus on greenhouse gas and NH_3 emissions from slurry management. Greenhouse gas emissions are characterized in terms of GWP_{100}, expressed as kg CO_2-equivalents per functional unit. The latest IPCC assessment values are used for GWP_{100} – for example, methane's characterization factor is ~28 based on the IPCC AR6 (2021) recommendation, reflecting its 100-year warming effect relative to CO_2. All relevant GHG emissions in the model (enteric CH_4, manure CH_4 and N_2O, fertiliser and energy-related emissions, etc.) are converted to CO_2-eq using these factors to compute an overall carbon footprint for each scenario (both in absolute terms and per kg FPCM).

NH_3 emissions are tracked as the key contributor to acidification and air pollution in this context. In the LCIA, NH_3 emissions are translated into an acidification potential impact, reported in kg SO_2-equivalent per functional unit, using the standard characterisation factors from the CML baseline method (2001) for acidifying substances. This metric accounts for the potential of NH_3 to form acidifying compounds in ecosystems (via formation of ammonium and subsequent deposition). However, since the absolute quantity of NH_3 emitted is also of direct interest for compliance with air quality targets, results are additionally discussed in terms of total NH_3 emissions (e.g. kg NH_3 per year and per kg milk) for each system. Other impact categories such as eutrophication or acidfication were calculated in the broader LCA (following the methods described in Chapter 3), but the presentation of results in this chapter primarily centers on climate (GHG emissions) and ammonia-related impacts, as these are the areas most directly addressed by the slurry amendment intervention. All impact results are evaluated on a per-functional unit basis to enable direct comparison between the Shinagh scenario (with and without additive) and the conventional farm scenario.

The LCIA thus translates the inventoried emissions and resource use into relevant environmental impact indicators, which are presented and discussed in Section 5.5. Any assumptions and uncertainties in the impact calculations, for instance, the effectiveness of the additive or variability in emission factors, are examined in the sensitivity analyses to ensure confidence in the comparative findings.

1.4 Results and Discussion

1.4.1 Trial Results

The controlled slurry amendment trial demonstrated substantial reductions in greenhouse gas and ammonia emissions from stored dairy slurry. Over the 56-day experiment, the treated slurry's cumulative biogas production was reduced by 73.1% compared to the untreated control, indicating a major suppression of anaerobic decomposition. Correspondingly, the methane (CH_4) content in biogas fell markedly: total CH_4 emissions from the treated slurry were 79.0% lower than the control over the trial period. This dramatic mitigation of CH_4 is attributed to the oxidative action of the hydrogen peroxide (H_2O_2)-based additive, which introduced more aerobic conditions in the slurry and inhibited methanogenic archaea (Kavanagh et al., 2021). By curtailing microbial breakdown of organic matter, the amendment effectively hindered the methanogenesis pathway, yielding an almost five-fold decrease in CH_4 generation relative to untreated slurry.

In addition to curbing methane, the additive virtually eliminated ammonia (NH_3) volatilization during storage. In the treated slurry, NH_3 emissions were almost entirely abated (approaching a 100% reduction in NH_3 loss) compared to the control. This outcome is exceptionally high relative to previous studies: for example, Kavanagh et al. (2019a) reported about a 96% reduction in NH_3 emissions using strong acid amendments, and Brennan et al. (2015) observed roughly a 54% reduction with a chemical amendment. The near-complete abatement of NH_3 emissions observed in the present trial suggests that the H_2O_2-based additive may act primarily through biochemical inhibition of microbial or enzymatic processes, rather than acidification. Specifically, the suppression of urease activity, the enzyme responsible for converting urea into NH_3, appears a likely pathway, as previously proposed in the literature (Thorn et al., 2022). This interpretation is further supported by the fact that pH values in treated slurry did not decrease over time, and in some cases increased slightly (see Table 5.3), indicating that pH shifts are unlikely to be the main mitigation mechanism in this context. The reduction in NH_3 is also evident from the higher nitrogen content in the day 56| post-trial treated slurry which was 2.18% greater than in the untreated slurry. Retaining more nitrogen in the manure is beneficial, as it can improve the fertiliser value of the slurry when applied to land. There was no statistically significant change in slurry phosphorus content between treated and control samples over the trial. This suggests that the amendment did not affect phosphorus dynamics in the stored manure, which is consistent with expectations, as phosphate compounds are non-volatile and not subject to gaseous loss during storage.

Overall, the trial's results demonstrate that chemical amendment of dairy slurry with an oxidizing additive can achieve simultaneous, significant mitigation of both CH_4 and NH_3 emissions during storage. Such dual mitigation is critical, as it avoids the trade-off often seen in manure management where reducing NH_3 via acidification can inadvertently increase CH_4, or vice versa (Brennan et al., 2015).

1.4.2 Shinagh Farm

To understand the practical significance of these experimental findings, the effects of the slurry additive were integrated into a life cycle assessment (LCA) of a real-world dairy system (Shinagh Farm). Shinagh Farm's 2022 baseline (without the additive) provides a point of comparison for emissions and environmental impacts. Under baseline management, the farm's total annual greenhouse gas emissions were 1,121 tonnes CO_2-equivalent (CO_2-eq). Allocating these emissions between milk and meat co-products on a biophysical basis, approximately 79–80% of the impacts were assigned to milk production, corresponding to a carbon footprint of 0.675 kg CO_2-eq per kg of FPCM (fat-and-protein-corrected milk) in 2022. This value reflects a relatively efficient dairy production system. Enteric fermentation from the herd was the dominant source of greenhouse gases, accounting for about 67.7% of the farm's GWP (approximately 0.458 kg CO_2-eq per kg FPCM). Manure management, in contrast, contributed a smaller share of emissions: roughly 9–10% of the total GWP (~0.06–0.07 kg CO_2-eq per kg FPCM) was attributable to manure handling (including emissions from manure excreted on pasture, stored in tanks, and land-applied). The remaining GHG emissions arose from feed concentrate production (~10% of total emissions), synthetic fertiliser manufacture and use (~10%), with minor contributions from on-farm energy use (fuel and electricity ~1.5% combined) and other inputs like lime, bedding plastic, and contractor services (each <1%). Consistent with these proportions, the majority of Shinagh's GHG emissions (about 80%) occur directly on the farm, while roughly 15–20% are from upstream production of inputs (feed, fertiliser, etc.).

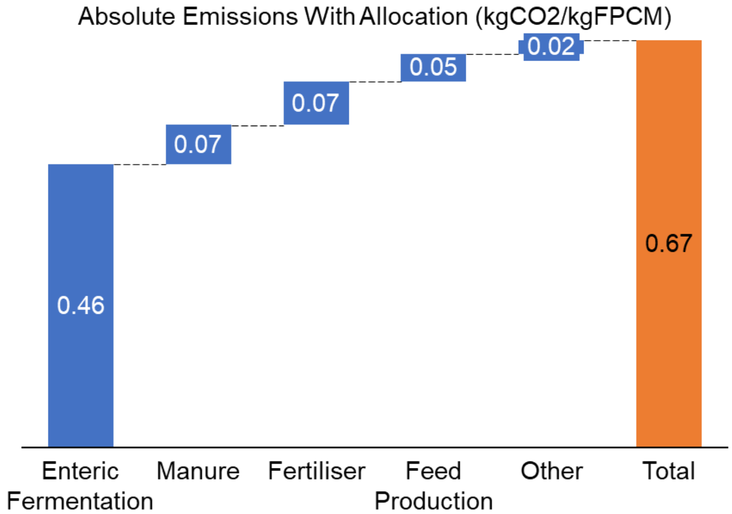

Figure 5.5: Shinagh Farm 2022 - GWP Emissions

Ammonia emissions at Shinagh Farm were also quantified to establish the baseline acidification potential. Annual NH_3 emissions from the farm were estimated at approximately 2,794 kg NH_3, translating to 2.11 g NH_3 per kg FPCM after allocation to milk. These NH_3 emissions predominantly originated from manure management processes. In the baseline scenario, manure deposited by cows on pasture during grazing accounted for the largest fraction of NH_3 loss (~43% of total NH_3 emissions), since urea in urine quickly volatilizes when left on fields. The next major source was initial manure storage during housing (slatted sheds or holding tanks), responsible for roughly one-third (~34%) of the NH_3 emissions. Subsequent storage in the slurry tank (approximately a three-month storage period at Shinagh) contributed about 13% of NH_3 emissions, and emissions during land spreading of slurry accounted for the remaining ~9%. Fertiliser-related NH_3 losses were minimal (~1%) at Shinagh, because this farm's strategy already involved efficient fertiliser use and low-emission slurry spreading techniques. The overall acidification potential (AP) indicator for Shinagh's milk production was calculated as 1.73 g SO_2-equivalent per kg FPCM (8.6×10^{-4} mol H^+-eq), reflecting the combined impact of all NH_3 sources and other acidifying emissions.

With this baseline established, the experimentally observed mitigation effects of the slurry additive were applied to Shinagh Farm's manure management system in the LCA model. In practice, this means adjusting the farm's manure storage emission factors to reflect a ~79% reduction in CH_4 and a 100% reduction in NH_3 during the storage period for the treated portion of slurry. (It is important to note that the baseline manure emissions in the LCA were derived from standard inventory methods consistent with national guidelines and the Chapter 4 results, rather than directly from the trial's control measurements. This approach ensured that the farm-scale analysis remained aligned with real farm conditions – accounting for Shinagh's actual slurry volume and storage duration – while using the trial's relative mitigation efficacy to scale down those emissions in the additive scenario.) After incorporating the additive's effects, the modeled greenhouse gas emissions from manure storage at Shinagh were substantially lower. Methane emissions from the slurry during storage resulted the manure management stage's GWP being reduced by about 67% compared to the baseline. This result highlights how effective the additive is in the context of the farm's GHG profile: whereas untreated manure management contributed nearly 10% of total GWP, in the additive scenario that contribution was only around 3%. Notably, this level of mitigation far exceeds what has been reported with some other slurry amendments in the literature. For instance, Borgonovo et al. (2019) evaluated a commercial slurry additive and found only a 16.7% reduction in manure-related GWP, due to an unintended increase in CH_4 emissions during their treatment. In contrast, the H_2O_2-based amendment in the present study avoids such trade-offs and achieves a much greater proportional reduction in stored manure emissions.

In terms of ammonia, implementing the slurry additive at Shinagh Farm also markedly decreased NH_3 volatilization during storage. In the model, ammonia emissions from the slurry storage phase (the tank storage) were virtually eliminated – a 100% reduction in NH_3 from that stage – consistent with the trial observations (see Table 5.4). This translates to a substantial retention of nitrogen in the stored manure. However, when considering the farm system as a whole, the fate of that extra nitrogen must be accounted for: what is not lost in storage may be lost later when the slurry is applied to land. In the additive scenario, because the treated slurry retained more nitrogen, the model projected a 3.3% increase in NH_3 emissions during the land-spreading stage, from 242.3 kg to 250.4 kg NH_3 per year, as a result of higher volatilisation potential upon field application. This is a minor trade-off resulting from the shifted timing of emissions – nitrogen conserved through storage tends to elevate volatilization potential upon spreading if not managed with improved application techniques.

At Shinagh, slurry is already applied using a low-emission method (trailing shoe), which minimises NH_3 losses at spreading. As a result, the absolute increase in NH_3 emissions was relatively small, only around 8 additional kilograms per year. More importantly, the additional nitrogen retained in the slurry enabled the substitution of approximately 92.9 kg of synthetic nitrogen fertiliser, reducing the farm's overall fertiliser demand. This substitution led to a 0.6% reduction in GHG emissions from fertiliser production and application, and a 1.0% reduction in fertiliser-derived NH_3 emissions. Even though these offsets were modest, they contributed positively to the farm's environmental profile. Thus, while the additive slightly increased NH_3 emissions at the spreading stage, this was offset by lower fertiliser-related emissions, resulting in a net benefit in terms of both nitrogen efficiency and climate impact. These findings highlight the importance of evaluating mitigation outcomes at the whole-farm level, as environmental gains at one stage can be counterbalanced by trade-offs at another. This reflected the net effect of major NH_3 reductions during storage, balanced against minor increases in NH_3 emissions during land-spreading.

After accounting for all these changes, the overall environmental performance of Shinagh Farm improved with the slurry additive, albeit modestly. The whole-farm carbon footprint (per kg of milk) was reduced by about 2.0%, from 0.675 to 0.661 kg CO_2-eq per kg FPCM. This net improvement might seem small in percentage terms, but it is important to recognize that manure storage emissions were only a minor portion of the farm's total GHG profile to begin with; even eliminating nearly all emissions from that stage yields only a few percent change in the total footprint because enteric fermentation remains the dominant source. Nonetheless, a 2% reduction at the farm scale is non-trivial given the challenge of cutting agricultural emissions. Furthermore, the farm's acidification potential showed a slightly larger relative improvement. The total AP for milk production dropped by about 3.2%, from 1.73 to roughly 1.67 g SO_2-eq/kg FPCM, in the additive scenario. In practical terms, the slurry amendment could help the farm marginally reduce its contributions to regional ammonia pollution and associated impacts (eutrophication, soil acidification), complementing Shinagh's existing low-emission spreading practice. These farm-scale results confirm that while the slurry additive yields significant reductions at the source (the storage tank), the translation to overall farm sustainability is noticeable but limited by the fact that other emission sources (especially enteric CH_4) remain unabated.

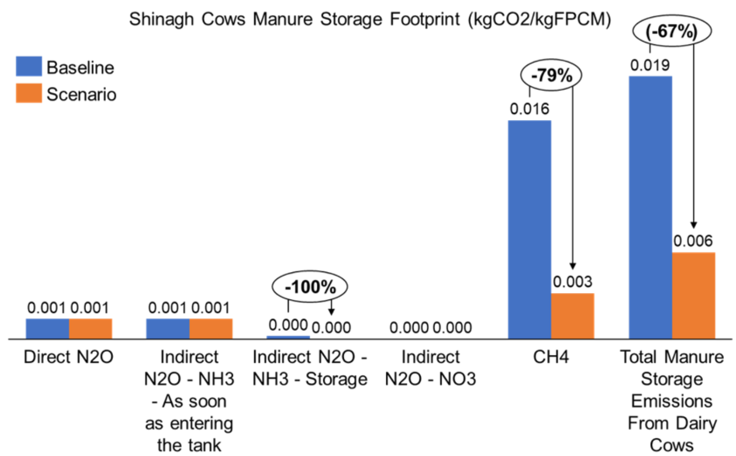

Figure 5.6: Shinagh Farm 2022 - Slurry Chemical Amendment Mitigation Potential on Manure

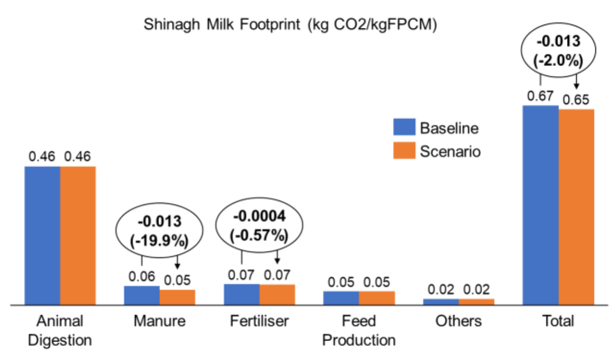

Figure 5.7: Shinagh Farm 2022 - Slurry Chemical Amendment Mitigation Potential on Farm

1.4.3 Conventional Farm

The impact of the slurry amendment was also evaluated under a representative conventional Irish dairy farm scenario to gauge how the results might differ in a less emissions-efficient system. In contrast to Shinagh's intensive, grass-based system with climate-mitigating practices, the conventional farm was assumed to have more typical management: higher reliance on imported feed, a shorter grazing season (and thus longer housing period), and standard slurry handling and spreading methods (e.g. roughly six months of storage and broadcast spreading). The baseline carbon footprint for the conventional farm was estimated at 0.93 kg CO_2-eq per kg FPCM, considerably higher than Shinagh's 0.67 kg. This higher GHG intensity arises from multiple factors. Notably, manure management emissions in the conventional scenario were about 1.86 times higher than those at Shinagh (approximately 0.13 kg CO_2-eq/kg FPCM from manure vs. 0.07 at Shinagh). The conventional farm keeps cattle housed for extended periods, requiring around six months of slurry storage over winter, as opposed to Shinagh's three-month storage regime. Longer storage leads to significantly greater CH_4 generation – according to IPCC (2019) guidelines, a 6-month storage can emit roughly 21% of the volatile solids as CH_4, whereas a 3-month storage emits around 12%. This difference in manure management practices (compounded by less frequent slurry agitation or the absence of additives) explains much of the manure-related GHG gap between the farms. Additionally, the conventional system likely uses more concentrate feed and fertiliser per unit of milk (due to lower nutrient use efficiency and a shorter grazing season), which contributes to its larger overall emissions.

Baseline ammonia emissions and acidification impacts are also higher in the conventional scenario. Total NH_3 emissions are about 2,246 kg NH_3 per year for a farm of comparable output, equivalent to 3.96 g NH_3 per kg FPCM – nearly double the NH_3 intensity at Shinagh. The distribution of NH_3 sources in a typical conventional system is different as well: land spreading of slurry tends to be a dominant source of NH_3 loss. In this scenario, roughly 29% of NH_3 emissions came from slurry application to land (reflecting the use of splash-plate spreading on most of the slurry). Initial housing and on-farm manure storage emissions constituted around 43% of total NH_3 (about 23% from the housing/storage pit and 10% from the long-term tank storage), while manure left on pasture contributed only ~20% (because cows graze for a shorter portion of the year). Fertiliser application accounted for about 18% of NH_3 emissions – higher than at Shinagh, since the conventional farm uses more chemical N overall. The overall acidification potential for the conventional milk was correspondingly high, around 4.7 g SO_2-eq/kg FPCM (2.3×10^{-3} mol H^+-eq), underlining how standard practices can lead to substantial NH_3 emissions.

Applying the slurry additive in the conventional farm model yielded significant emission reductions in magnitude, though directionally similar results to the Shinagh case. Because the conventional farm's baseline manure emissions were larger, the absolute benefits of mitigation were greater. With the additive implemented (assuming it is added to the stored slurry to achieve ~79% CH_4 reduction and ~100% NH_3 reduction during storage, as in the trial), the GWP from manure management dropped sharply. In fact, the manure-related GWP in the conventional scenario fell by approximately 23% relative to its baseline value for that component – a slightly larger proportional reduction than the ~20% observed at Shinagh. This was expected, as a higher fraction of the conventional farm's total emissions came from the treatable source (slurry CH_4) that the additive targets.

Conversely, the reduction in GHG emissions from fertiliser production was smaller in the conventional farm model, amounting to only 0.4%, compared to 0.6% at Shinagh. This difference reflects the higher baseline use of synthetic nitrogen fertiliser in the conventional system, where offsetting 92.9 kg of synthetic N with conserved manure-N accounts for a smaller proportional change. Moreover, the use of splash-plate slurry spreading technology, which is less efficient than the trailing shoe method used at Shinagh, resulted in greater NH_3 volatilisation during land application. Specifically, NH_3 emissions during spreading increased by 3.0%, rising from 655.0 to 674.6 kg NH_3 per year in the additive scenario. This increase was a direct consequence of more nitrogen being retained during storage and subsequently lost under inefficient field application. As a result, while the shift from synthetic to manure-derived nitrogen reduced CO_2 emissions from fertiliser manufacture, the concurrent increase in NH_3 emissions during spreading partially offset this benefit. This trade-off illustrates the importance of pairing nitrogen conservation strategies with low-emission application technologies to capture the full mitigation potential..

When all effects are taken into account, the slurry amendment was estimated to reduce the total carbon footprint of the conventional farm by about 3.2%. This brings the footprint down from 0.93 to roughly 0.90 kg CO_2-eq per kg milk – a meaningful improvement for a single intervention, though the conventional farm would still remain higher-emitting than Shinagh's baseline due to other management differences. This slightly larger percentage reduction (3.2% vs 2.0% at Shinagh) highlights that conventional farms tend to benefit more from slurry-based mitigation technologies, not only because they have greater baseline emissions from manure management, but also because they lack other efficiency measures, such as precision spreading or optimised fertiliser regimes, that are already in place at more advanced farms like Shinagh. As such, manure emission mitigation technologies can deliver relatively larger gains where broader management practices remain less optimised.

Model outputs showed that NH_3 emissions from the long-term slurry storage stage dropped from roughly 225 kg to 138 kg per year (a ~39% reduction in that stage's NH_3, which is slightly less than full abatement, reflecting that not all slurry fractions or storage phases may receive treatment in practice). NH_3 emissions from synthetic fertiliser use also declined marginally, from 409.9 to 407.2 kg, due to partial substitution of chemical nitrogen with retained slurry nitrogen. However, NH_3 emissions from land application of slurry increased from 655.0 to 674.6 kg—a 3.0% rise—driven by the higher nitrogen content of the treated slurry and the continued use of splash-plate spreading, which is less efficient than the trailing-shoe method used at Shinagh.

This shift in emissions illustrates a redistribution rather than an elimination of nitrogen losses. Although the additive conserved nitrogen during storage, a portion of this nitrogen was subsequently lost during field application due to the low effectiveness of the spreading method. The net result across the storage, fertiliser, and spreading stages was an increase of 16.9 kg NH_3 per year. Meanwhile, greenhouse gas emissions from fertiliser production decreased by 0.4%, reflecting the relatively small impact of substituting a fixed amount of chemical nitrogen in a system with high baseline fertiliser use.

The cumulative effect of these interactions was a 2.8% reduction in AP per kg FPCM. Although this is a meaningful improvement, it is slightly lower than the 3.2% reduction observed at Shinagh. This difference can be attributed to the more effective slurry management practices at Shinagh—particularly the use of low-emission spreading—and its lower baseline reliance on synthetic fertiliser. In contrast, the conventional farm experienced greater field-level NH_3 losses, which reduced the overall system-level benefit. These findings reinforce the importance of integrating slurry treatment technologies with complementary practices, such as precision application, to maximise environmental gains across both air quality and acidification impact categories.

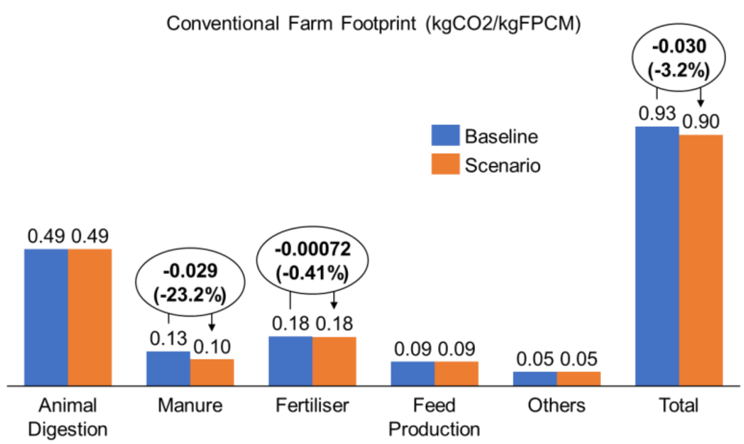

Figure 5.8: Conventional Farm - Slurry Chemical Amendment Mitigation Potential on Farm

1.4.4 System-Level NH_3 Emissions: Source Attribution and Net Effects

This section provides a system-level comparison of NH_3 emissions across key emission stages for both the Shinagh additive scenario and the conventional farm model, consolidating results that were previously discussed across multiple sections. By attributing NH_3 emissions to their sources—housing, storage, land-spreading, pasture, and fertiliser application—it is possible to better understand the distribution, magnitude, and trade-offs of emissions across the two systems.

In the conventional farm scenario, NH_3 emissions were heavily concentrated in housing and storage. Approximately 43% of total NH_3 originated from these two phases, with 23% from housing and short-term pit storage, and a further 20% from long-term uncovered slurry tank storage. Manure deposited on pasture accounted for around 20% of total NH_3, reflecting the shorter grazing season. Fertiliser application contributed the remaining 18%, which was notably higher than at Shinagh due to greater synthetic N use. This emissions profile resulted in an acidification potential of 4.7 g SO_2-eq per kg FPCM, or 2.3×10^{-3} mol H^+-eq, indicating the substantial impact of standard practice.

In contrast, the Shinagh additive scenario achieved near-complete mitigation of NH_3 from slurry storage, due to the application of a H_2O_2-based chemical amendment during winter housing. However, this N retention led to a 3.3% increase in NH_3 during land-spreading, rising from 242.3 to 250.4 kg NH_3 per year, due to the higher volatilisation potential of the nutrient-rich slurry. Because Shinagh already employs low-emission spreading (trailing shoe), the absolute increase was small—only 8.1 kg NH_3 per year. The additional retained N enabled the substitution of 92.9 kg of synthetic N fertiliser, leading to a 0.6% reduction in CO_2 emissions from fertiliser production and a 1.0% reduction in fertiliser-derived NH_3 emissions. NH_3 from pasture was approximately 43%, consistent with Shinagh's extended grazing season.

Taken together, these results show that while NH_3 increased slightly at spreading, the total emissions remained stable, with offsets occurring through storage abatement and reduced fertiliser use. The strategy improved whole-farm N efficiency and delivered a modest net GHG reduction. This highlights the importance of evaluating NH_3 outcomes systemically, recognising both mitigation gains and emissions redistribution.

1.4.5 Sensitivity and Uncertainty Analysis

The robustness of these findings was examined through sensitivity and uncertainty analysis, recognizing several limitations in the data and assumptions. For the slurry storage trial, one uncertainty was the intermittent sampling schedule. Slurry chemical properties (e.g. pH, sulfur content, nitrogen content) were only measured on days 1, 28, and 56. This limited temporal resolution means that any short-term fluctuations in these parameters, including potential transient changes in pH following additive application, were not captured. Notably, the available measurements do not indicate a sustained reduction in pH, suggesting that pH suppression was unlikely to be the primary mechanism for ammonia mitigation. Instead, the observed NH_3 reductions are more plausibly explained by alternative pathways such as microbial inhibition or urease suppression, which align with mechanisms proposed in previous studies on hydrogen peroxide-based slurry amendments. Future trials should incorporate more frequent sampling or continuous monitoring to better characterise the dynamic chemical and microbiological effects of slurry treatment over time.

On the farm-scale LCA side, uncertainties stem from farm data inputs and emission factor choices. Key farm activity data such as exact grazing duration, feed intake per cow, and manure excretion rates were based on farm records and standard coefficients, which have inherent variability. Improvements in on-farm measurements (for example, using pasture sensors for grazing time, in-silo feed weighing systems for concentrate use, or flow meters on manure tanks) could increase the accuracy of the inventory and thus the precision of the LCA results.

Methodological choices in the LCA can also influence the outcomes significantly, as revealed by sensitivity tests. We explored how results change under different emissions accounting approaches. For instance, using Intergovernmental Panel on Climate Change Tier 2 emission factors (generic national averages) in place of the more detailed, farm-specific factors in our baseline led to noticeable shifts in the calculated emissions. Specifically, when we applied Tier 2 factors for manure N_2O emissions on well-drained Irish pasture instead of Shinagh's disaggregated values, the manure-related N_2O estimate increased and raised the farm's total GWP from about 0.67 to ~0.69 kg CO_2-eq/kg milk (roughly a 3% increase in the overall footprint). Similarly, using Tier 2 default factors for synthetic fertiliser N_2O emissions (in lieu of accounting for the farm's specific fertiliser regime) increased the direct N_2O emissions from fertiliser application from ~0.07 to 0.12 kg CO_2-eq/kg FPCM. These variations underscore how sensitive the results are to the emission factor assumptions. In contrast, choosing different reputable life cycle inventory data sources for upstream processes (for example, comparing the International Fertiliser Society dataset versus the Ecoinvent database for fertiliser production emissions) produced minimal differences in total GHG results – on the order of 1–2% change in those components. The largest methodological influence observed was indeed related to emission factor selection for on-farm processes, especially enteric fermentation and manure management. Our use of an IPCC Tier 3 (country-specific) model for enteric CH_4 yielded a slightly higher enteric emission estimate than a simpler Tier 2 approach would (about 0.52 vs 0.46 kg CO_2-eq/kg milk, respectively), highlighting that more granular models can yield divergent absolute values.

Another aspect of uncertainty is the representativeness of national inventory factors for a specific farm like Shinagh. We found that if we ignored the farm's particular conditions and instead used undifferentiated Irish average factors for manure and fertiliser emissions, the calculated GWP of Shinagh Farm would increase substantially (by roughly 12.8%). This indicates that Shinagh's actual management is better than the national average (e.g. due to well-timed fertiliser applications and good soil conditions), and using generic averages would overestimate its emissions. It also means that the potential benefit of the slurry additive could be misrepresented if one does not account for specific farm context. Therefore, the study emphasizes the importance of refining Ireland's National Inventory Report methodology to incorporate more farm-specific parameters (such as seasonal housing effects and soil drainage classes), as national aggregates may not adequately capture the variability in manure and fertiliser management. Improving data precision and methodological consistency in this way would enhance the reliability of environmental impact assessments for mitigation strategies.

Hotspot	GHG	GHG Uncertainty of activity data	Uncertainty of emission factor
Enteric fermentation while on a silage diet	CH_4	40.7%	11.0%
Enteric fermentation while on a non-silage diet	CH_4	40.7%	20.0%
Manure left on pasture direct emissions	N_2O	47.6%	40.9%
Fertiliser application direct emissions	N_2O	47.6%	15.0%

Table 5.3: Shinagh Farm 2022 - Uncertainty Assessment Parameters

1.4.6 Implications

The integrated results and discussion above highlight that chemical slurry amendments, such as the H_2O_2-based additive tested, can play a useful role in mitigating environmental impacts in Irish dairy farming. At the slurry storage level, this technology offers a highly effective means of reducing two important emissions (methane and ammonia) simultaneously. This is particularly relevant for Ireland as it strives to meet ambitious greenhouse gas reduction targets (a 25% cut in agricultural emissions by 2030 relative to 2018 levels) while also adhering to ammonia emission ceilings under EU law. The additive's dual mitigation means it could help address climate and air quality objectives in tandem. For example, if all dairy farms in Ireland adopted this additive, the cumulative GHG reduction could reach an estimated 176,000 tonnes CO_2-eq per year – about 0.77% of agricultural emissions (0.29% of national emissions) based on our conventional farm scenario. While modest relative to sector-wide targets, this contribution would still represent meaningful progress towards climate goals.

Moreover, by retaining more nitrogen in manure, slurry amendments such as the hydrogen peroxide-based treatment can contribute to more circular and efficient nutrient management. In the conventional farm scenario, the additive led to a reduction of 87.1 kg NH_3 per year from storage, which, if applied across similar farms at scale, could make a meaningful contribution toward national ammonia reduction targets under the National Emissions Ceilings Directive. However, the benefit depends significantly on how the treated slurry is subsequently applied. In the model, the use of splash-plate spreading technology resulted in an increase of 19.6 kg NH_3 per year from land-spreading, as the nitrogen retained during storage became more prone to volatilisation upon field application. As a result, the net reduction in NH_3 emissions was 67.5 kg per year in the conventional farm scenario. This highlights that while additive technologies improve nitrogen retention, their full benefit is only realised when paired with low-emission spreading methods such as trailing shoe or injection. Without this integration, a portion of the retained nitrogen is lost downstream, diminishing both the air quality and fertiliser substitution benefits.

However, the findings also indicate that while beneficial, slurry amendment is not a standalone solution for decarbonizing dairy. Even with near-complete elimination of storage emissions, the overall carbon footprint reduction was only a few percent in our scenarios. The bulk of emissions in grass-based dairy systems comes from enteric methane; thus, tackling enteric CH_4 (through feed additives, breeding, or management) remains crucial. Nonetheless, a few-percent reduction at the farm scale is valuable when combined with other measures – in a sector facing stringent climate targets, incremental gains from multiple interventions will be necessary. Additionally, reducing ammonia emissions from agriculture has co-benefits for ecosystem health (less nitrogen deposition) and human health (less particulate matter formation from ammonia-derived aerosols), which are not fully captured by GWP metrics but are important from a policy standpoint.

The contrast between Shinagh and the conventional farm scenario highlights the importance of tailoring mitigation strategies to the specific management context of each farm. Farms that have not yet implemented foundational measures—such as extended grazing, improved slurry storage, or low-emission spreading—stand to gain relatively more from introducing slurry additives, both in terms of emission reductions and improved nitrogen retention. However, retaining more nitrogen in slurry also increases the risk of NH_3 volatilisation during land application, especially if the farm continues to use high-loss methods like splash-plate spreading. To fully realise the benefits of additive technologies, they must therefore be combined with precision spreading techniques that minimise downstream NH_3 losses. On the other hand, farms that already operate with low baseline emissions—such as Shinagh—may adopt additives for more targeted improvements, for example to address localised air quality concerns near sensitive receptors. More broadly, the widespread adoption of such technologies can help the Irish dairy sector demonstrate credible progress on sustainability, enhancing both regulatory compliance and public trust. Ongoing refinement and on-farm validation of slurry amendment strategies will be essential to unlock their full potential in contributing to Ireland's ammonia and greenhouse gas reduction targets, while supporting the resilience of pasture-based dairy systems.

1.5 Conclusion

The rapid expansion of Ireland's dairy sector has heightened the urgency of addressing emissions from manure management. This study applied a LCA to evaluate the environmental effects of a hydrogen peroxide-based slurry additive trialled under commercial conditions at Shinagh Farm. Results from the controlled storage trial showed a substantial reduction in CH_4 emissions (–79.04%) and complete abatement of ammonia NH_3 volatilisation. Treated slurry also retained 2.18% more nitrogen, offering potential to reduce synthetic fertiliser demand when land-applied, with additional environmental benefits.

When scaled to the whole-farm level, the additive reduced Shinagh's carbon footprint by 2.0%, lowering the global warming potential (GWP) from 0.67 to 0.65 kg CO_2-eq per kg of FPCM and decreased AP by 3.2% (from 1.73 to 1.67 g SO_2-eq/kg FPCM). In a conventional farm scenario with higher baseline emissions, the relative GWP reduction was even greater (–3.2%), while the reduction in AP was more modest (–2.8%). Extrapolated nationally, widespread adoption of the additive could yield an estimated 176 kilotonnes of CO_2-equivalent savings annually, representing 0.29% of Ireland's total GHG emissions and 0.77% of emissions from the agricultural sector.

In terms of ammonia, the additive could also contribute directly to Ireland's compliance with its national ammonia ceiling of 116,000 tonnes per year. Based on modelled results, NH_3 reductions from slurry storage ranged from 87 to 138 kg NH_3 per farm per year, depending on the baseline system. Assuming adoption across Ireland's 17,500 dairy farms, this equates to a national reduction of approximately 1,400 to 2,400 tonnes of NH_3 annually, or 1.2–2.1% of the national ceiling. These figures underscore the value of integrating slurry amendment strategies into broader air quality and nutrient management policies. However, the actual benefit depends on concurrent use of low-emission spreading methods, without which a significant portion of retained nitrogen may be lost during land application.

These results confirm that targeted manure management technologies can contribute to national climate and air quality goals, especially when deployed alongside other mitigation strategies. While the additive's impact on total farm emissions is modest, it addresses a specific emission hotspot without inducing pollution swapping. Further research is needed to assess long-term effects on soil health, nutrient cycling, and crop productivity under field conditions, as well as to evaluate cost-effectiveness and farmer adoption potential.

In summary, chemical slurry amendments offer a practical and impactful way to reduce emissions from dairy systems. As pressure grows to decarbonise Irish agriculture, such interventions—when supported by empirical trials and system-level modelling—can help align productivity with environmental goals. However, further trials in full-scale manure storage systems are needed to confirm effectiveness under real-world conditions. To maximise benefits, especially the retained nitrogen, additives should be paired with low-emission spreading technologies to avoid increased NH_3 losses at application. These steps are essential to fully realise the additive's contribution to Ireland's GHG and ammonia reduction targets.

Appendix A: Supplementary Information for Chapter 4

Table 9.1: Appendix - Chapter 4: Primary Inputs Data Quality Assessment

Parameter	TIR	TER	GR	P
% of supply chain	3	1	1	1
Breed	3	1	1	1
Number of lactating cows	3	1	1	1
Age at first calving	3	1	1	1
Replacement rate	3	1	1	1
Dairy farm area	3	1	1	1
Manure management system	3	1	1	1
Feed for lactating cows as grazed grass	3	1	1	1
Feed for lactating cows as hay or haylage	3	1	1	1
Feed for lactating cows as grass silage	3	1	1	1
Feed for lactating cows as maize silage	3	1	1	1
Feed for lactating cows as wheat silage	3	1	1	1
Feed for lactating cows as soybean meal	3	1	1	1
Feed for lactating cows as compound feed	3	1	1	1
Feed for lactating cows as agricultural by-products	3	1	1	1
Feed for heifers and dry cows as grazed grass	3	1	1	1
Feed for heifers and dry cows as hay or haylage	3	1	1	1
Feed for heifers and dry cows as grass silage	3	1	1	1
Feed for heifers and dry cows as maize silage	3	1	1	1
Feed for heifers and dry cows as wheat silage	3	1	1	1
Feed for heifers and dry cows as soybean meal	3	1	1	1
Feed for heifers and dry cows as compound feed	3	1	1	1
Feed for heifers and dry cows as agricultural by-products	3	1	1	1
Milk powder for calves	3	1	1	1

Bedding materials	3	1	1	1
Drinking water	3	5	5	5
Cleaning water	3	5	5	5
Electricity used on farm (for general operations vs. for dairy cattle)	3	1	1	1
Fuel oil used on farm (for general operations vs. for dairy cattle)	3	1	1	1
Natural gas used on farm (for general operations vs. for dairy cattle)	3	1	1	1
Milk production (total sold)	3	1	1	1
Milk fat content	3	1	1	1
Milk protein content	3	1	1	1
Production of cull cows sold to slaughter or further fattening	3	1	1	1
Production of calves sold for further fattening	3	1	1	1

Table 9.2: Appendix - Chapter 4: Secondary Inputs Data Quality Assessment

Substance	Process	TIR	TER	GR	P
Water	Irrigation water	5	5	5	5
	Drinking water	5	5	5	5
Land occupation and transformation	Feed production	1	1	1	2
	Grazing	1	1	1	1
CH_4 emitted to air	Enteric fermentation	2	1	1	1
	Manure storage	2	1	1	1
	Manure storage	2	1	1	1
Direct N_2O emitted to air	Manure excretion in the pasture	2	1	1	1
	Manure application	2	1	1	1
	Nitrogen fertiliser application	1	1	1	1
	Crop residues	5	5	5	5
	Organic soils	5	5	5	5
	Mineral soils	1	1	1	1
Indirect N_2O due to N volatilisation emitted to air	Manure storage	2	1	1	1
	Manure application	2	1	1	1
	Manure excretion in the pasture	2	1	1	1
	Nitrogen fertiliser application	1	1	1	1
Indirect N_2O due to N leaching emitted to air	Manure application	2	1	1	1
	Manure excretion in the pasture	2	1	1	1
	Nitrogen fertiliser application	1	1	1	1
	Crop residues	5	5	5	5
NH_3 and nitric oxides emitted to air	Manure storage	2	1	1	1
	Manure application	2	1	1	1
	Manure excretion in the pasture	2	1	1	1
	Nitrogen fertiliser application	1	1	1	1
Phosphate emitted to ground and surface water	Manure application	2	1	1	1
	Manure excretion in the pasture	2	1	1	1
	Artificial fertiliser application	1	1	1	1
Phosphorus emitted to surface water	Manure application	2	1	1	1
	Manure excretion in the pasture	2	1	1	1
	Artificial fertiliser application	1	1	1	1
Particulate matter emitted to air	Animal housing	1	1	1	1
	Silage feeding	2	1	1	1
Non-CH_4 volatile solids	Housing	1	1	1	1
	Grazing	2	1	1	1

	Manure application	1	1	1	1
Nitrate emitted to ground water	Manure excretion in the pasture	1	1	1	1
	Nitrogen fertiliser application	1	1	1	1
	Crop residues	5	5	5	5
CO_2 emitted to air	Application of lime	1	1	1	1
	Application of urea	1	1	1	1
	Peat drainage	5	5	5	5
	Fuel combustion	1	1	1	1
Heavy metals emitted to groundwater and soil	Application of manure	2	1	1	1
Pesticides, emitted to soil	Application of pesticides	5	5	5	5

Table 9.3: Appendix - Chapter 4: Activity Data and Emissions Factors for LCA Model

Source of Emissions	Method used for calculating emissions
CH_4 from enteric fermentation when no silage is fed	kg CH_4 = (Gross Energy Intake MJ * (Ym/100)) / 55.65 (Intergovernmental Panel on Climate Change, 2019a) Ym = 6.3 (-) (Intergovernmental Panel on Climate Change, 2019a) 55.65 = Energy content of CH_4 (MJ/kg CH_4) (Intergovernmental Panel on Climate Change, 2019a)
CH_4 from enteric fermentation when silage is fed	kg CH_4 = (Digestible Energy Intake MJ * (0.035 * (silage intake kg DM/total intake kg DM)) - (2.298 * (feeding level -1))) / 55.65 (Yan et al., 2000) FL = total net energy requirement / maintenance net energy requirement (INRA, 1989; Yan et al., 2004)

Continued on next page

CH_4 from manure	kg CH_4 = volatile solids kg * (Bo * 0.67 * (MCF/100)) (Intergovernmental Panel on Climate Change, 2019a) Housing Bo = 0.24 m^3 CH_4/kg VS (Intergovernmental Panel on Climate Change, 2019a) Grazing Bo = 0.19 m^3 CH_4/kg VS (Intergovernmental Panel on Climate Change, 2019a) Pit storage for 3 months MCF = 12% (Intergovernmental Panel on Climate Change, 2019a) Solid storage MCF = 2% (Intergovernmental Panel on Climate Change, 2019a) Pasture MCF = 0.47% (Intergovernmental Panel on Climate Change, 2019a)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
Direct N_2O from manure left on pasture	kg N_2O = manure left on pasture kg N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EFs used are for well drained soils EF for Spring Urine: = 0.32 kg N_2O-N/kg N EF for Summer Urine = 0.31 kg N_2O-N/kg N EF for Autumn Urine = 0.30 kg N_2O-N/kg N EF for Spring Dung = 0.03 kg N_2O-N/kg N EF for Summer Dung = -0.02 kg N_2O-N/kg N EF for Autumn Dung = 0.13 kg N_2O-N/kg N (Krol et al., 2016)
NH_3 from manure left on pasture	kg NH_3-N = manure left on pasture kg N * TAN, % * EF (Misselbrook & Gilhespy, 2020) EF = 6% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020) TAN, % = 60%

Continued on next page

Indirect N_2O from manure left on pasture due to atmospheric deposition	kg N_2O = manure left on pasture kg NH_3-N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EF = 1% kg N_2O-N/kg NH_3-N (Intergovernmental Panel on Climate Change, 2019b)
NO_3 from manure left on pasture	kg NO_3-N = manure left on pasture kg N * FracLeach FracLeach = 10% kg NO_3-N/kg N (Ryan, 2006)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
Indirect N_2O from manure left on pasture due to leaching	kg N_2O = manure left on pasture kg NO_3-N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EF = 1.1% kg N_2O-N/kg NO_3-N (Environmental Protection Agency, 2021; Intergovernmental Panel on Climate Change, 2019b)
NO from manure left on pasture	kg NO-N = manure left on pasture kg N * EF EF = 4% kg NO-N/kg N (Environmental Protection Agency, 2018; European Environment Agency, 2019)
P_2O_5 leaching to groundwater	kg P_2O_5 = 0.07 * (chemical fertiliser kg P_2O_5 + slurry or liquid manure kg P_2O_5 + solid manure kg P_2O_5) (Nemecek et al., 2007)
P_2O_5 run-off to surface waters	kg P_2O_5 = 0.25 * 1 + {((0.2/80) * chemical fertiliser kg P_2O_5) + ((0.7/80) * slurry or liquid manure kg P_2O_5) + ((0.4/80) * solid manure kg P_2O_5)} (Nemecek et al., 2007)

Continued on next page

NH_3 from manure management - as soon as entering the tank	kg NH_3-N = manure entering the tank kg N * TAN,% * EF (Misselbrook & Gilhespy, 2020) TAN,% = 60% (Misselbrook & Gilhespy, 2020) Dairy cows liquid manure EF = 27.7% kg NH_3-N/kg N (Misselbrook & Gilh- espy, 2020) Replacements liquid manure EF = 27.7% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
	Replacements solid manure EF = 4.2% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020)
Indirect N_2O from manure as soon as entering the tank due to atmospheric deposition	kg N_2O = manure entering the tank kg NH_3-N * EF * (44/28) (Intergovern- mental Panel on Climate Change, 2019b) EF = 1% kg N_2O-N/kg NH_3-N (Intergovernmental Panel on Climate Change, 2019b)
Direct N_2O from manure management	kg N_2O = (manure entering the tank kg N - NH_3 from manure management as soon as entering the tank kg NH_3-N) * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019a) Pit storage EF = 0.002 kg NO_2-N/kg N (Intergovernmental Panel on Climate Change, 2019a) Solid storage EF = 0.010 kg N_2O-N/kg N (Intergovernmental Panel on Climate Change, 2019a)

Continued on next page

NH_3 from manure management	kg NH_3-N = (manure entering the tank kg N - NH_3 from manure management as soon as entering the tank kg NH_3-N) * TAN,% * EF (Intergovernmental Panel on Climate Change, 2019a) TAN, % = 64% (Misselbrook & Gilhespy, 2020) Covered liquid manure systems EF = 10% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
	Uncovered liquid manure systems EF = 5% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020) Solid manure systems EF = 35% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020)
Indirect N_2O from manure management due to atmospheric deposition	kg N_2O = manure storage kg NH_3-N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019a) EF = 1% kg N_2O-N/kg NH_3-N (Intergovernmental Panel on Climate Change, 2019a)
NO_3 from manure management	kg NO_3-N = (manure entering the tank kg N - NH_3 from manure management as soon as entering the tank kg NH_3-N) * FracLeach Pit storage FracLeach = 0% kg NO_3-N/kg N Solid storage FracLeach = 0% kg NO_3-N/kg N
Indirect N_2O from manure management due to leaching	kg N_2O = manure storage kg NO_3-N * EF * (44/28) EF = 1.1% kg N_2O-N/kg N (Intergovernmental Panel on Climate Change, 2019b)

Continued on next page

N_2 from manure management	kg N_2-N = (manure entering the tank kg N - NH_3 from manure management as soon as entering the tank kg NH_3-N) * TAN,% * EF (European Environment Agency, 2019)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
	TAN, % = 64% Liquid manure EF = 0.3% kg N_2-N/kg N (European Environment Agency, 2019) Solid manure EF = 30% kg N_2-N/kg N (European Environment Agency, 2019)
NO from manure management	kg NO-N = (manure entering the tank kg N - NH_3 from manure management as soon as entering the tank kg NH_3-N) * TAN,% * EF (European Environment Agency, 2019) TAN, % = 64% Liquid manure EF = 0.01% kg NO-N/kg N (European Environment Agency, 2019) Solid manure EF = 1% kg NO-N/kg N (European Environment Agency, 2019)
Direct N_2O from manure land spreading	Slurry applied to soils kg N = manure entering the tank kg N - NH_3 from manure management as soon as entering the tank kg NH_3-N - NH_3 from manure management kg NH_3-N - NO_3 from manure management kg NO_3-N - N_2 from manure management kg N_2-N - NO from manure management kg NO-N kg N_2O = slurry applied to soils kg N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EF = 0.6% kg N_2O-N/kg N (Intergovernmental Panel on Climate Change, 2019b)

Continued on next page

NH_3 from manure land spreading	kg NH_3-N = slurry applied to soils kg N * TAN,% * EF (Misselbrook & Gilhespy, 2020) TAN, % = 60% (Misselbrook & Gilhespy, 2020)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
	Trailing shoe liquid manure spring EF = 10.4% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020) Trailing shoe liquid manure summer EF = 19.
NH_3 from manure land spreading	kg NH_3-N = slurry applied to soils kg N * TAN,% * EF (Misselbrook & Gilhespy, 2020) TAN, % = 60% (Misselbrook & Gilhespy, 2020) Trailing shoe liquid manure spring EF = 10.4% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020) Trailing shoe liquid manure summer EF = 19.4% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020) Trailing shoe liquid manure autumn EF = 13.7% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020) Solid manure EF = 68.3% kg NH_3-N/kg N (Misselbrook & Gilhespy, 2020)

Continued on next page

Indirect N_2O from land spreading due to atmospheric deposition	kg N_2O = slurry applied to soils kg NH_3-N * EF * (44/28) EF = 1% kg N_2O-N/kg NH_3-N (Intergovernmental Panel on Climate Change, 2019b)
NO_3 from manure land spreading	kg NO_3-N = slurry applied to soils kg N * FracLeach FracLeach = 10% kg NO_3-N/kg N (Ryan, 2006)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
Indirect N_2O from manure land spreading leaching	kg N_2O = slurry applied to soils kg NO_3-N * EF * (44/28) EF = 1.1% kg N_2O-N/kg NO_3-N (Intergovernmental Panel on Climate Change, 2019b)
NO from manure land spreading	kg NO-N = slurry applied to soils kg N * EF EF = 4% kg NO-N/kg N (European Environment Agency, 2019)
Direct N_2O from chemical fertiliser	kg N_2O = chemical fertiliser kg N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EF for well drained soils CAN EF = 0.87% kg N_2O-N/kg N (Harty et al., 2016) Urea EF = 0.18% kg N_2O-N/kg N (Harty et al., 2016) Protected urea EF = 0.41% kg N_2O-N/kg N (Harty et al., 2016)

Continued on next page

NH_3 from chemical fertiliser	kg NH_3-N = chemical fertiliser kg N * EF (Intergovernmental Panel on Climate Change, 2019b) CAN EF = 0.0065 kg NH_3-N/kg N (Environmental Protection Agency, 2018) Urea EF = 0.1278 kg NH_3-N/kg N (Environmental Protection Agency, 2018) NPK Mixtures EF = 0.0123 kg NH_3-N/kg N (Environmental Protection Agency, 2018) Protected urea EF = 0.0271 kg NH_3-N/kg N (Environmental Protection Agency, 2018)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
Indirect N_2O from chemical fertiliser due to atmospheric deposition	kg N_2O = chemical fertiliser kg NH_3-N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EF = 1% kg N_2O-N/kg NH_3-N (Intergovernmental Panel on Climate Change, 2019b)
NO_3 emissions from chemical fertiliser	kg NO_3-N = chemical fertiliser kg N * FracLeach (Intergovernmental Panel on Climate Change, 2019b) FracLeach = 10% kg NO_3-N/kg N (Ryan, 2006)
Indirect N_2O emissions from chemical fertiliser due to leaching	kg N_2O = chemical fertiliser kg NO_3-N * EF * (44/28) (Intergovernmental Panel on Climate Change, 2019b) EF = 1.1% kg N_2O/kg NH_3-N (Intergovernmental Panel on Climate Change, 2019b)
NO from chemical fertiliser	kg NO-N = chemical fertiliser kg N * EF (European Environment Agency, 2019) EF = 4% kg NO-N/kg N (European Environment Agency, 2019)

Continued on next page

CO_2 due to urea fertil-isation	kg CO_2 = urea spread kg * 0.2 * (44/12) (Intergovernmental Panel on Climate Change, 2019b)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
CO_2 from fertiliser production containing nitrogen	kg CO_2 = fertiliser applied kg N * EF EF for European fertiliser CAN EF = 3.523 kg CO_2/kg N (Hoxha & Christensen, 2018) Urea EF = 3.502 kg CO_2/kg N (Hoxha & Christensen, 2018) Ammonium Nitrate EF = 3.319 kg CO_2/kg N (Hoxha & Christensen, 2018)
CO_2 from fertiliser production not containing nitrogen	kg CO_2 = fertiliser applied kg P * EF Phosphorus fertiliser EF = 1.726 kg CO_2/kg P
CO_2 from feed production	kg CO_2 = ingredient kg * EF EF = Sourced from Agri-Footprint 6 using an economic allocation
CO_2 from lime application	kg CO_2 = limestone applied kg * 0.12 * (44/12) (Intergovernmental Panel on Climate Change, 2019b)

Continued on next page

CO_2 from electricity production	kg CO_2 = electricity consumption kWh * EF EF = 0.72 kg CO_2/kWh (AIB, 2019)
CO_2 from diesel production	kg CO_2 = diesel consumed L * EF EF = 2.56 kg CO_2/L (Sustainable Energy Authority of Ireland, 2022)

Continued on next page

Table 9.3 – *Continued from previous page*

Source of Emissions	Method used for calculating emissions
CO_2 from machinery use	kg CO_2 = machinery consumption MJ * EF EF = 0.069 kg CO_2/MJ sourced from Ecoinvent

Bibliography

- Agri-Footprint, 2023. Agri-footprint. URL: https://www.agri-footprint.com/
- AIB, 2019. European residual mixes 2018 association of issuing bodies description of the document URL: , doi:.
- Alignier, Audrey & Uroy, Léa. (2020). The role of hedgerows in supporting biodiversity and other ecosystem services in intensively managed agricultural landscapes.
- Almeida, A.K., Hegarty, R.S., Cowie, A., 2021. Meta-analysis quantifying the potential of dietary additives and rumen modifiers for CH_4 mitigation in ruminant production systems. Animal Nutrition 7, 1219–1230. URL:
- Amon, B., Kryvoruchko, V., Amon, T. and Zechmeister-Boltenstern, S. (2006) 'CH_4, N_2O and NH_3 emissions during storage and after application of dairy cattle slurry and influence of slurry treatment', *Agriculture, Ecosystems & Environment*, 112(2–3), pp.153–162.
- Baldini, C., Gardoni, D. and Guarino, M., 2017. A critical review of the recent evolution of LCA applied to milk production. Journal of Cleaner Production, 140, pp.421–435.
- Barbara, K., 2022. Mapping the European Soy Supply Chain - Embedded Soy in Animal Products. Report. World Wide Fund for Nature (Germany). URL: https://policycommons.net/artifacts/2329550/mapping-the-european-soy-supply-chain/
- Barragán-Ocaña, A., Merritt, H., Sánchez-Estrada, O.E., Méndez-Becerril, J.L., Del Pilar Longar-Blanco, M., 2023a. Biorefinery and sustainability for the production of biofuels and value-added products: A trends analysis based on network and patent analysis. PLOS ONE 18, e0279659. https://doi.org/10.1371/journal.pone.0279659
- Barragán-Ocaña, A., Merritt, H., Sánchez-Estrada, O.E., Méndez-Becerril, J.L., del Pilar Longar-Blanco, M., 2023b. Biorefinery and sustainability for the production of biofuels and value-added products: A trends analysis based on network and patent analysis. PLOS ONE 18, e0279659. https://doi.org/10.1371/journal.pone.0279659
- Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J. and Wang, M. (2020) 'Review: Fifty years of research on rumen methanogenesis: Lessons learned and future challenges for mitigation', *Animal*, 14(S1), s2–s16.
- Berntsen, J, Grant, R, Olesen, JE, Kristensen, IS, Vinther, FP, Mølgaard, JP & Petersen, BM 2006, 'Nitrogen cycling in organic farming systems with rotational grass-clover and arable crops', Soil Use and Management, vol. 22, pp. 197-208. <http://www.blackwell-synergy.com/doi/abs/10.1111/j.1475-2743.2005.00016.x>

- Bijelić, Z., Mandić, V., Ružić-Muslić, D., Krnjaja, V.S., Simić, A., Zivkovic, V., Caro-Petrovic, V. Evaluation of competitive ability of perennial ryegrass in mixtures with red clover and lucerne subjected to different levels of n.
- Blonk Agri-footprint BV (2019) Agri-footprint 5.0 – Part 2: Description of data. Gouda, The Netherlands.
- Bobbink, R., Hicks, W.K., Galloway, J.N., Spranger, T., Alkemade, R. et al. (2010) 'Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis', *Ecological Applications*, 20(1), pp. 30–59.
- Bord Bia (2023) *Performance and Prospects Report 2023*. Dublin: Bord Bia Irish Food Board.
- Borgonovo, F., Conti, C., Lovarelli, D., Ferrante, V., Guarino, M., 2019. Improving the sustainability of dairy slurry by a commercial additive treatment. doi:10.3390/su11184998.
- Bragaglio, A., Braghieri, A., Pacelli, C., & Napolitano, F. (2020). Environmental Impacts of Beef as Corrected for the Provision of Ecosystem Services. Sustainability, 12(9), 3828. https://doi.org/10.3390/su12093828
- Brander, Matthew & Tipper, R. & Hutchison, Charlotte & Davis, G.. (2009). Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to GHG LCA of Biofuels. Ecometrica. Technical Paper TP090403A. 44.
- Brankatschk, Gerhard & Finkbeiner, Matthias. (2014). Application of the Cereal Unit in a new allocation procedure for agricultural LCAs. Journal of Cleaner Production. 73. 72–79. 10.1016/j.jclepro.2014.02.005.
- Brennan, R.B., Fenton, O., Rodgers, M., Richards, K.G. and Healy, M.G. (2015) 'Impact of chemical amendment of dairy cattle slurry on phosphorus, nitrogen and carbon losses during rainfall events', *Journal of Environmental Management*, 146, pp.294–302.
- Brennan, R.B., Healy, M.G., Fenton, O., Lanigan, G.J., 2015. The effect of chemical amendments used for phosphorus abatement on GHG and NH_3 emissions from dairy cattle slurry: Synergies and pollution swapping. PLOS ONE 10, e0111965. https://doi.org/10.1371/journal.pone.0111965.
- Brennan, R.B., Healy, M.G., Fenton, O., Lanigan, G.J., 2015. The effect of chemical amendments used for phosphorus abatement on GHG and NH_3 emissions from dairy cattle slurry: Synergies and pollution swapping. PLOS ONE 10, e0111965. https://doi.org/10.1371/journal.pone.0111965
- Brito, A.F., Silva, L.H.P., 2020. Symposium review: Comparisons of feed and milk nitrogen efficiency and carbon emissions in organic versus conventional dairy production systems. Journal of Dairy Science 103, 5726–5739. URL: , doi:https://doi.org/10.3168/jds.2019-17232.

- Bryant, R.H., Miller, M.E., Greenwood, S.L., Edwards, G.R., 2017. Milk yield and nitrogen excretion of dairy cows grazing binary and mul- tispecies pastures. Grass and Forage Science 72, 806–817. URL: , doi:.
- Bryant, R.H., Miller, M.E., Greenwood, S.L., Edwards, G.R., 2017. Milk yield and nitrogen excretion of dairy cows grazing binary and multispecies pastures. Grass and Forage Science 72, 806–817. http://doi.wiley.com/10.1111/gfs.12274
- Buckley, C. and Donnellan, T., 2022. Teagasc National Farm Survey 2021 Sustainability Report. Agricultural Economics and Farm Surveys Department, Rural Economy and Development Programme, Teagasc, Athenry, Co. Galway, Ireland. ISBN: 978-1-84170-681-8. Available at: https://www.teagasc.ie/media/website/publications/2022/2021-Sustainability-Report.pdf
- Buckley, C., 2022. Teagasc National Farm Survey 2021 Sustainability
- Buckley, C., Donnellan, T., 2020. Teagasc national farm survey 2018 sustainability report .
- Buckley, C., Donnellan, T., 2023. Teagasc National Farm Survey 2022 Sustainability Report. Report. https://www.teagasc.ie/media/website/publications/2023/SustainabilityReport2022.pdf.
- Buckley, C., Wall, D.P., Moran, B. et al. Farm gate level nitrogen balance and use efficiency changes post implementation of the EU Nitrates Directive. Nutr Cycl Agroecosyst 104, 1–13 (2016). https://doi.org/10.1007/s10705-015-9753-y
- Burton, R.J.F. (2004) 'Seeing through the 'good farmer's' eyes: Towards developing an understanding of the social symbolic value of 'productivist' behaviour', *Sociologia Ruralis*, 44(2), pp.195–215.
- Cantarella, H., Otto, R., Soares, J.R., Silva, A.G.d.B., 2018. Agronomic efficiency of nbpt as a urease inhibitor: A review. Journal of Advanced Research 13, 19–27. https://doi.org/10.1016/j.jare.2018.05.008
- Cantarella, H., Otto, R., Soares, J.R., Silva, A.G.d.B., 2018. Agronomic efficiency of nbpt as a urease inhibitor: A review. Journal of Advanced Research 13, 19–27. URL:
- Capper, J.L. and Cady, R.A. (2020) 'A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production', *Journal of Dairy Science*, 103(1), pp.515–531.
- Carswell, A., et al., 2022. Combining targeted grass traits with red clover improves grassland performance and reduces need for nitrogen fertilisation. European Journal of Agronomy 133. https://doi.org/10.1016/j.eja.2021.126433
- Carswell, A., et al., 2022. Combining targeted grass traits with red clover improves grassland performance. European Journal of Agronomy 133. https://doi.org/10.1016/j.eja.2021.126433
- Carswell, A., Sánchez-Rodríguez, A.R., Saunders, K., le Cocq, K., Shaw, R., Cotton, J., Zhang, Y., Evans, J., Chadwick, D.R., Jones, D.L., Misselbrook, T., 2022. Combining targeted grass traits with

red clover improves grassland performance and reduces need for nitrogen fertilisa- tion. European Journal of Agronomy 133, 126433–126433. URL:

- Casey, J.W. and Holden, N.M. (2005) 'Analysis of GHG emissions from the average Irish milk production system', *Agricultural Systems*, 86(1), pp.97–114.
- Central Statistics Office (CSO) (2021) *Farm Structure Survey 2020*. Dublin: Government of Ireland.
- Central Statistics Office (CSO) (2023) *Livestock and Milk Statistics 2022*. Dublin: Government of Ireland.
- Central Statistics Office Ireland, ., 2011. Output, input and income in agriculture URL: .
- Central Statistics Office Ireland, ., 2021. Output, input and income in agriculture
- Central Statistics Office Ireland, 2011. Output, input and income in agriculture. www.cso.ie
- Central Statistics Office Ireland, 2021. Output, input and income in agriculture. https://www.cso.ie/en/releasesandpublications/er/oiiaf/outputinputandincomeinagriculture-finalestimate2021/
- Cherubini, F. and Ulgiati, S. (2010) 'Crop residues as raw materials for biorefinery systems – A LCA case study', *Applied Energy*, 87(1), pp.47–57.
- CJ, O.F., Healy, M.G., Lanigan, G.J., Troy, S.M., Somers, C., Fenton, O., 2013. Impact of chemically amended pig slurry on GHG emissions, soil properties and leachate. J Environ Manage 128, 690–8. doi:10.1016/j.jenvman.2013.06.020.
- CJ, O.F., Healy, M.G., Lanigan, G.J., Troy, S.M., Somers, C., Fenton, O., 2013. Impact of chemically amended pig slurry. J Environ Manage 128, 690–8. https://doi.org/10.1016/j.jenvman.2013.06.020
- Clark, M. A., Domingo, N. G. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., Azevedo, I. L., & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science (New York, N.Y.), 370(6517), 705–708. https://doi.org/10.1126/science.aba7357
- Clavin, D., Crosson, P., Grant, J., O'Kiely, P., 2017. Red clover for silage: management impacts on herbage yield, nutritive value, ensilability and persistence, and relativity to perennial ryegrass. Grass and Forage Science 72, 414–431. URL: , doi:.
- Clavin, D., et al., 2016. Red clover for silage: Management impacts on herbage yield, nutritive value, ensilability and persistence. Grass and Forage Science 72. doi:10.1111/gfs.12249
- Clavin, D., et al., 2017. Red clover for silage: management impacts on herbage yield, nutritive value, ensilability and persistence. Grass and Forage Science 72, 414–431. https://doi.org/10.1111/gfs.12249
- Climate Action Plan 2021. Report.

- Congio, G., et al., 2021. Enteric CH_4 mitigation strategies. Journal of Cleaner Production 312, 127693. https://doi.org/10.1016/j.jclepro.2021.127693
- Connolly, J., 2009. Effects of multi-species swards on dry matter production and the incidence of unsown species at three irish sites. URL: .
- Connolly, J., 2009. Effects of multi-species swards on dry matter production. https://www.researchgate.net/publication/236583514_
- Connolly, S., O'Flaherty, V. and Krol, D.J. (2023) 'Inhibition of CH_4 production in cattle slurry using an oxygen-based amendment', Journal of Cleaner Production, 394, 136272. doi:10.1016/j.jclepro.2023.136272
- Copland, A (2020) *The Common Agricultural Policy Post-2020*. Kilcoole: BirdWatch Ireland.
- Costigan, H., et al., 2024. The impact of 3-nitroxypropanol supplementation on enteric CH_4 emissions. Journal of Dairy Science. https://www.sciencedirect.com/science/article/pii/S0022030224009007
- Creamer RE, Hannula SE, Leeuwen J, Stone D, Rutgers M, Schmelz RM, De Ruiter P, Hendriksen N, Bolger T, Bouffaud ML, Buee M, Carvalho F, Costa D, Dirilgen T, Francisco R, Griffiths BS, Griffiths R, Martin F, Silva PD, Mendes S, Morais PV, Pereira C, Philippot L, Plassart P, Redecker D, Römbke J, Sousa JP, Wouterse M, Lemanceau P. (2016) Ecological network analysis reveals the inter-connection between soil biodiversity and ecosystem function as affected by land use across Europe. Appl. Soil Ecol.97:112-124.
- Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G.J., Foley, P.A. and Boland, T.M. (2011) 'A review of whole farm systems models of GHG emissions from beef and dairy cattle production systems', *Animal Feed Science and Technology*, 166–167, pp.29–45.
- Cso, 2021. Output, input and income in agriculture. https://www.cso.ie/en/releasesandpublications/er/oiiaf/outputinputandincomeinagriculture-finalestimate2021/
- CSO, 2022. Output, input and income in agriculture - final estimate 2022.
- Cummins, S., Lanigan, G.J., Richards, K.G., Boland, T.M., Kirwan, S.F., Smith, P.E., Waters, S.M., 2022. Solutions to enteric CH_4 abate- ment in ireland. Irish Journal of Agricultural and Food Research 61
- Curran, M., De Baan, L. and Hellweg, S. (2011) 'Towards meaningful end points of biodiversity in LCA', *Environmental International*, 37(7), pp. 1303–1312.
- Curran, M.A. (2012) 'LCA: A review of the methodology and its application to sustainability', *Current Opinion in Chemical Engineering*, 1(3), pp.273–277.

- da Fonseca, A.B., Santos, C., Nunes, A.P.P., Oliveira, D.P., de Melo, M.E.A., Takayama, T., Mansur, B.L., de Jesus Fernandes, T., do Carmo Alexandrino, G., Dias, M.A.N., Guelfi, D., 2023. Urease in-hibitors technologies as strategy to mitigate agricultural NH_3 emis- sions and enhance the use efficiency of urea-based fertilisers. Scientific Reports 13, 22739. URL: , doi:.
- Dalby, Frederik & Guldberg, Lise & Feilberg, Anders & Kofoed, Michael. (2022). Reducing GHG emissions from pig slurry by acidification with organic and inorganic acids. PLOS ONE. 17. e0267693. 10.1371/journal.pone.0267693.
- Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N.J., Jacobsen, B.H., Kronvang, B., Olesen, J.E. and Schjørring, J.K. (2014) 'Policies for agricultural nitrogen management – trends, challenges and prospects for improved efficiency in Denmark', *Environmental Research Letters*, 9(11), 115002.
- De Klein, Cecile & Monaghan, Ross. (2011). The effect of farm and catchment management on nitrogen transformations and N_2O losses from pastoral systems — can we offset the effects of future intensification?. Current Opinion in Environmental Sustainability. 3. 396–406. 10.1016/j.cosust.2011.08.002.
- De La Torre-Santos, S., Royo, L.J., Martínez-Fernández, A., Chocarro, C., Vicente, F., 2020. The mode of grass supply to dairy cows impacts on fatty acid and antioxidant profile of milk. Foods 9, 1256. URL: , doi:.
- Department of Agriculture Food & the Marine, 2022. Low emission slurry spreading (less) equipment scheme. URL: .
- Department of the Environment Climate & Communications, ., 2022b. Sectoral Emissions Ceilings. Report. URL:
- Department of Agriculture, Food and the Marine (2023) *Agri-Climate Rural Environment Scheme (ACRES)*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (2023) *Ireland's CAP Strategic Plan 2023–2027*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2015) *Food Wise 2025: A 10-Year Strategy for the Irish Agri-Food Sector*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2020) *Ag Climatise: A Roadmap Towards Climate Neutrality*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2021) *Food Vision 2030: A World Leader in Sustainable Food Systems*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2022) *Fifth Nitrates Action Programme*. Dublin: Government of Ireland.

- Department of Agriculture, Food and the Marine (DAFM) (2022) *Food Vision 2030 Progress Report*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2022) *Ireland's CAP Strategic Plan 2023–2027*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2023) *Annex of Actions for Climate and Nature*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2023) *Climate Action Plan 2023: Agriculture Sectoral Pathway*. Dublin: Government of Ireland.
- Department of Agriculture, Food and the Marine (DAFM) (2023) Renewable Heat Obligation Scheme Consultation. Government of Ireland.
- Department of the Environment Climate & Communications, ., 2021.
- Department of the Environment Climate & Communications, ., 2022a. An Overview of Ireland's Fifth Nitrates Action Programme. Report. URL: .
- Department of the Environment Climate & Communications, 2022b. Sectoral Emissions Ceilings. https://www.gov.ie/pdf/?file=https://assets.gov.ie/234926/2ebb2431-d558-4a54-a15c-605817c37b2f.pdf#page=null.
- Department of the Environment, Climate and Communications (DECC) (2023) *Climate Action Plan 2023*. Dublin: Government of Ireland.
- Di, H.J. and Cameron, K.C. (2012) 'How does the application of different nitrogen fertilisers affect N_2O emissions from grazed grassland?', *Agriculture, Ecosystems & Environment*, 159, pp.103–112.
- Díaz de Otálora, X., del Prado, A., Dragoni, F., et al. (2024). Modelling the effect of context-specific GHG and nitrogen emission mitigation options in key European dairy farming systems. Agronomy for Sustainable Development, 44(1), 4. https://doi.org/10.1007/s13593-023-00940-6
- Dijkstra, J., Bannink, A., France, J., Kebreab, E. and van Gastelen, S. (2018) 'Short communication: Prediction of enteric CH_4 production from lactating dairy cows using 3-nitrooxypropanol', *Journal of Dairy Science*, 101(5), pp.4463–4467.
- Dijkstra, J., et al., 2018. Antimethanogenic effects of 3-nitrooxypropanol. J Dairy Sci 101, 9041–9047. https://doi.org/10.3168/jds.2018-14456
- Dillon, E. J., Hennessy, T. and Hynes, S. (2010) 'Assessing the sustainability of Irish agriculture', International Journal of Agricultural Sustainability, 8(3), pp. 131–147. doi: 10.3763/ijas.2009.0044.
- Dillon, E., Donnellan, T., Moran, B., Lennon, J., 2022. Teagasc national farm survey 2021 .
- Dillon, E., et al., 2022. Teagasc national farm survey 2021.

- Dillon, P., Crosse, S., Stakelum, G. and Flynn, F. (2008) 'The effect of grazing intensity and grazing season length on grass and animal performance', *Grass and Forage Science*, 63(3), pp.337–349.
- Donnellan T, Hanrahan K. and Lanigan, G.J. (2018). Future Scenarios for Irish Agriculture: Implications for GHG and NH_3 Emissions. Teagasc, Oak Park, Carlow Ireland
- Donnellan, T., et al., 2015. The end of the quota era: A history of the Irish dairy sector.
- Donnellan, T., Hanrahan, K. and Lennon, J. (2021) *Teagasc Outlook 2021: Economic Prospects for Agriculture*. Teagasc, Rural Economy Development Programme.
- Donnellan, T., Hennessy, T., Thorne, F., 2015. The end of the quota era: A history of the irish dairy sector and its future prospects .
- Donnellan, T., Moran, B., Lennon, J., Dillon, E., 2019. Teagasc National Farm Survey 2019. Report. URL: .
- DSM, 2022. Dsm receives landmark eu market approval for its CH_4-reducing feed additive bovaer®. URL: .
- Duffy, P., Hanley, E., Black, K. and O'Brien, P. (2020) *National Inventory Report 2020: GHG Emissions 1990–2018*. Environmental Protection Agency, Wexford.
- Duffy, P., Hanley, E., Hyde, B. and Commins, V. (2020) *Ireland's National Inventory Report 2020*. Dublin: EPA Ireland.
- Duffy, P., Hyde, B., Hanley, E., et al. (2023) 'Ireland's National Inventory Report 2023', Environmental Protection Agency, Wexford.
- Duffy, P., Hyde, B., Hanley, E., O'Brien, P. and Black, K. (2020) Ireland's National Inventory Report 2020. Environmental Protection Agency, Johnstown Castle, Wexford.
- Duffy, P., Hyde, B., Ryan, A.M. and Alam, M.S. (2020) 'National Inventory Report 2020: GHG Emissions 1990–2018', *Environmental Protection Agency*, Wexford, Ireland.
- Duin, E.C., Wagner, T., Shima, S., Prakash, D., Cronin, B. et al. (2016) 'Mode of action uncovered for the specific reduction of CH_4 emissions from ruminants', *Proceedings of the National Academy of Sciences*, 113(22), pp.6172–6177.
- EC-JRC (2010) International Reference Life Cycle Data System (ILCD) Handbook—General Guide for LCA—Detailed Guidance. European Commission, Joint Research Centre, Ispra, Italy.
- ECHA (2023) Hydrogen peroxide: Classification and labelling according to CLP Regulation. European Chemicals Agency. Available at: https://echa.europa.eu/
- Ecoinvent (2021) *Ecoinvent Database v3.8 – System Models and Allocation*. Zurich: Ecoinvent Centre.

- Egan, M., et al., 2018. Incorporating white clover into perennial ryegrass swards receiving varying levels of nitrogen fertiliser: Effects on milk and herbage production. Journal of Dairy Science 101, 3412–3427. doi:10.3168/jds.2017-13233
- Egan, M., et al., 2018. Incorporating white clover into perennial ryegrass. Journal of Dairy Science 101, 3412–3427. https://doi.org/10.3168/jds.2017-13233
- Egan, M., Galvin, N., Hennessy, D., 2018. Incorporating white clover (trifolium repens l.) into perennial ryegrass (lolium perenne l.) swards receiving varying levels of nitrogen fertiliser: Effects on milk and herbage production. Journal of Dairy Science 101, 3412–3427. doi: .
- El bied, O., et al., 2023. Mitigating NH_3, CH_4, and CO_2 from slurry. https://doi.org/10.3390/w15234185
- El bied, O., Turbí, M.A., García-Valero, A., Cano, F., Acosta, J.A., 2023. Mitigating NH_3, CH_4, and carbon dioxide emissions from stored pig slurry using chemical and biological additives. doi:10.3390/w15234185.
- Elliot, C., Krol, D., Laughlin, R.J., Richards, K.G., Lanigan, G.J., 2016. Reducing N_2O emissions by changing n fertiliser use from calcium ammonium nitrate (can) to urea based formulations. Science of the Total Environment 563-564, 576–586. doi: .
- Elliott, J. and Image, M. (2017) 'Design of Agri-Environmental Schemes – evidence from the monitoring and evaluation of GLAS in Ireland', AgEcon Search. Available at: https://ageconsearch.umn.edu/record/276181/files/Design%20of%20Agri-Environmental%20Schemes%20%E2%80%93%20evidence%20from%20the%20monitoring%20and%20evaluation%20GLAS%20in%20Ireland.pdf.
- Emmet-Booth, J.P., Dekker, S., and O'Brien, P., 2019. Climate Change Mitigation and the Irish Agriculture and Land Use Sector. [pdf] Climate Change Advisory Council. Available at: https://www.climatecouncil.ie/councilpublications/councilworkingpaperseries/Working%20Paper%20No.%205.pdf
- Englund, O., et al., 2022. Large-scale deployment of grass in crop rotations as a multifunctional climate mitigation strategy. GCB Bioenergy 15, 166–184.
- Enriquez-Hidalgo, D., et al., 2016. Herbage and nitrogen yields from white clover. Grass and Forage Science 71, 559–574. https://doi.org/10.1111/GFS.12201
- Enriquez-Hidalgo, D., et al., 2016. Herbage and nitrogen yields, fixation and transfer by white clover to companion grasses. Grass and Forage Science 71, 559–574. doi:10.1111/GFS.12201
- Enriquez-Hidalgo, D., Gilliland, T.J., Hennessy, D., 2016. Herbage and nitrogen yields, fixation and transfer by white clover to companion grasses in grazed swards under different rates of nitrogen fertilisation. Grass and Forage Science 71, 559–574. doi:.

- Environmental Protection Agency (2023) *Ireland’s National Inventory Report 2023: GHG Emissions 1990–2021*. Wexford: EPA.
- Environmental Protection Agency (EPA) (2020) *State of the Environment Report 2020*. Wexford: EPA.
- Environmental Protection Agency (EPA) (2022) *State of the Environment Report 2020*. Wexford: EPA.
- Environmental Protection Agency (EPA) (2022) *Water Quality in 2020: An Indicators Report*. Johnstown Castle, Co. Wexford: EPA.
- Environmental Protection Agency (EPA) (2022a) *Ireland’s Air Pollutant Emissions 2021*. Johnstown Castle, Co. Wexford: EPA.
- Environmental Protection Agency (EPA) (2023) *Air Pollutant Emissions 2022*. Johnstown Castle, Co. Wexford: EPA.
- Environmental Protection Agency (EPA) (2023) *Ireland's Environment: An Integrated Assessment 2023*. Wexford: EPA.
- Environmental Protection Agency (EPA) (2023a) *Ireland’s Provisional GHG Emissions 1990–2022*. Johnstown Castle, Co. Wexford: EPA.
- Environmental Protection Agency (EPA) (2023b) *Ireland’s National Inventory Report 2023: GHG Emissions 1990–2021*. Wexford: EPA.
- Environmental Protection Agency, ., 2018. The environmental protection agency ireland’s informative inventory report 2018 air pollutant emis- sions URL: .
- Environmental Protection Agency, ., 2021. Ireland’s national inventory report 2021 URL: .
- Environmental Protection Agency, ., 2022. Ireland’s national inventory report 2022 URL: .
- Environmental Protection Agency, ., 2023. Ireland’s national inventory report 2023 .
- Environmental Protection Agency, 2018. Ireland’s Informative Inventory Report. www.epa.ie.
- Environmental Protection Agency, 2022. Ireland’s National Inventory Report 2022. www.epa.ie.
- Environmental Protection Agency, 2023. Ireland’s National Inventory Report 2023.
- "Eory, V., MacLeod, M., Topp, CFE., Rees, RM., Webb, J., McVittie, A., Wall, E., Borthwick, F., Watson, CA., Waterhouse, A., Wiltshire, J., Bell, H., Moran, D., & Dewhurst, RJ. (2015). Review and update the UK agriculture MACC to assess the abatement potential for the 5th carbon budget period and to 2050: Final report submitted for the project contract “Provision of services to review and update the UK agriculture MACC and to assess abatement potential for the 5th carbon budget period and to 2050”. Prepared for the Climate Change Committee. https://www.theccc.org.uk/publication/scotlands-rural-collage-sruc-ricardo-energy-and-environment-2015-review-

- and-update-of-the-uk-agriculture-macc-to-assess-abatement-potential-for-the-fifth-carbon-budget-period-and-to-
- 2050/"
- Erisman, J.W., Bleeker, A., Galloway, J., Sutton, M.S. and Grizzetti, B. (2008) 'Reduced nitrogen in ecology and the environment', *Environmental Pollution*, 154(3), pp. 357–361.
- European Commission – Joint Research Centre (2010) *ILCD Handbook: General guide for LCA – Detailed guidance*. Luxembourg: Publications Office of the European Union.
- European Commission (2018) *Product Environmental Footprint (PEF) Guide*. Brussels: European Union.
- European Commission (2020) *A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system*. Brussels: European Union.
- European Commission (2022) 'National Emission reduction Commitments Directive reporting 2022', Brussels: Directorate-General for Environment.
- European Commission (2023) *Commission Implementing Decision (EU) 2023/164 on the derogation for Ireland under the Nitrates Directive*. Brussels: European Union.
- European Environment Agency (2023) *Annual European Union GHG inventory 1990–2021 and inventory report 2023*. Luxembourg: Publications Office of the European Union.
- European Environment Agency (EEA) (2021) Trends and projections in Europe 2021: Tracking progress towards Europe's climate and energy targets. EEA Report No 13/2021.
- European Environment Agency, ., 2019. Air pollutant emission inven- tory guidebook 2019. URL: .
- European Environment Agency, 2019. Air pollutant emission inventory guidebook 2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019
- European Food Safety Authority (EFSA) (2021) 'Scientific opinion on the safety and efficacy of 3-NOP as a feed additive for dairy cows', *EFSA Journal*, 19(6), e06544.
- European Parliament and Council (2021) *Regulation (EU) 2021/2115 establishing rules on CAP strategic plans*. Brussels: Official Journal of the European Union.
- F, Toner & J, Bowman & J, Clabby & Lucey, J. & Mcgarrigle, Martin & Concannon, C. & Clenaghan, C. & Cunningham, Peter & Delaney, J. & O'Boyle, Shane & MacCárthaigh, M. & Craig, M.. (2005). Water Quality in Ireland 2001-2003.
- FAO (2016) *Environmental Performance of Animal Feeding Operations: Guidelines for Ruminant Livestock Supply Chains*. Rome: Livestock Environmental Assessment and Performance (LEAP) Partnership.

- FAO (2019) *GHG emissions from the dairy sector: A LCA*. Rome: Food and Agriculture Organization of the United Nations.
- FAO (2021) 'Global assessment of soil carbon in grasslands', Food and Agriculture Organization of the United Nations, Rome.
- FAO (2023) Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations, Rome.
- Fealy, R.M., Buckley, C., Mechan, S., Melland, A.R. and Mellander, P.E. (2010) 'The Irish Agricultural Catchments Programme: Catchment selection using spatial multi-criteria decision analysis', *Soil Use and Management*, 26(3), pp.225–236.
- Fisher, M. and Rahmann, G. (1997) 'Extensification - benefits and disadvantages to grassland biodiversity', Conservation Evidence. Available at: https://www.conservationevidence.com/individual-study/3242.
- Fitzpatrick, U., Murray, T. E., Paxton, R. J., & Brown, M. J. (2007). Building on IUCN regional red lists to produce lists of species of conservation priority: a model with Irish bees. Conservation biology : the journal of the Society for Conservation Biology, 21(5), 1324–1332. https://doi.org/10.1111/j.1523-1739.2007.00782.x
- Flysjö, A., Cederberg, C., Henriksson, M. and Ledgard, S. (2011) 'How does co-product handling affect the carbon footprint of milk? Case study of dairy products from New Zealand and Sweden', *International Journal of LCA*, 16(5), pp.420–430.
- Flysjö, A., Cederberg, C., Henriksson, M. and Ledgard, S. (2011) 'The interaction between milk and beef production and emissions from land use change – critical considerations in LCA and carbon footprint studies of milk', *Journal of Cleaner Production*, 28, pp.134–142.
- Foereid, Bente & Szocs, Julia & Patinvoh, Regina & Sárvári Horváth, Ilona. (2020). Effect of anaerobic digestion of manure before application to soil – benefits for nitrogen utilisation?. International Journal of Recycling of Organic Waste in Agriculture. 10. 10.30486/ijrowa.2020.1897538.1055.
- Food Vision Dairy Group (2022) *Interim Report: Reducing GHG Emissions from the Dairy Sector*. Dublin: Government of Ireland.
- Fornara, D.A., et al., 2016. Carbon balance of permanent grassland. Biogeosciences 13, 4975–4984. https://bg.copernicus.org/articles/13/4975/2016/
- Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., McNeill, G., Chambers, B.J. and Richards, K.G. (2016), NH_3 emissions from urea, stabilized urea and calcium ammonium nitrate: insights into loss abatement in temperate grassland. Soil Use Manage, 32: 92-100. https://doi.org/10.1111/sum.12232

- Fowler, D., Steadman, C., Stevenson, D., Vieno, M., Simpson, D. and Sutton, M. (2020) 'Effects of land use and agricultural practices on atmospheric emissions and deposition of NH_3', *Philosophical Transactions of the Royal Society B*, 375(1794), 20190446.
- Gaffey, J., et al., 2023a. Synergetic benefits for a pig farm and local bioeconomy development from extended green biorefinery value chains. Sustainability 15, 8692. https://doi.org/10.3390/su15118692
- Gaffey, J., et al., 2023c. Green biorefinery systems for the production of climate-smart sustainable products from grasses. Biotechnology Advances 66, 108168. https://www.sciencedirect.com/science/article/pii/S0734975023000757
- Gaffey, James & Collins, Maurice. (2024). Review of methodological decisions in LCA of biorefinery systems across feedstock categories. Journal of Environmental Management. 348. 120813. 10.1016/j.jenvman.2024.120813.
- Garbach, K. et al. (2016) 'Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification', International Journal of Agricultural Sustainability, 15(1), pp. 11–28. doi: 10.1080/14735903.2016.1174810.
- Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G. (2013) *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organization of the United Nations.
- Government of Ireland (2021) *Climate Action and Low Carbon Development (Amendment) Act 2021*. Dublin: Stationery Office.
- Government of Ireland (2021) *Climate Action Plan 2021: Securing Our Future*. Dublin: Department of the Environment, Climate and Communications.
- Government of Ireland (2022) 'Climate Action Plan 2023', Department of the Environment, Climate and Communications, Dublin.
- Grace, C., Boland, T.M., Sheridan, H., Brennan, E., Fritch, R., Lynch, M.B., 2019. The effect of grazing versus cutting on dry matter production of multispecies and perennial ryegrass-only swards. Grass and Forage Science 74, 437–449. doi:.
- Green, R.E., Cornell, S.J., Scharlemann, J.P.W. and Balmford, A. (2005) 'Farming and the fate of wild nature', *Science*, 307(5709), pp.550–555.
- Groenestein, C.M., Hutchings, N.J., Haenel, H.D., Amon, B., Menzi, H., Mikkelsen, M.H., Misselbrook, T.H., van Bruggen, C., Kupper, T. and Webb, J., 2019. Comparison of NH_3 emissions related to nitrogen use efficiency of livestock production in Europe. Journal of Cleaner Production, 211, pp.1162–1170.
- Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., and Huijbregts, M.A.J. (2002)

Handbook on LCA: Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht.

- Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T. and Rydberg, T. (2011) 'LCA: Past, present, and future', *Environmental Science & Technology*, 45(1), pp.90–96.
- Harmsen, M., Tabak, C., Höglund-Isaksson, L., et al. (2023). Uncertainty in non-CO_2 GHG mitigation contributes to ambiguity in global climate policy feasibility. Nature Communications, 14, 2949. https://doi.org/10.1038/s41467-023-38577-4
- Harty, M.A., et al., 2016. Reducing N_2O emissions by changing N fertiliser use. Science of the Total Environment 563–564, 576–586. doi:10.1016/j.scitotenv.2016.04.120
- Harty, M.A., Forrestal, P.J., Watson, C.J., McGeough, K.L., Carolan, R., Elliot, C., Krol, D., Laughlin, R.J., Richards, K.G., Lanigan, G.J., 2016. Reducing N_2O emissions by changing n fertiliser use from calcium ammonium nitrate (can) to urea based formulations. Science of the Total Environment 563-564, 576–586. doi:10.1016/j.scitotenv. 2016.04.120.
- Hatfield, J.L., Johnson, D.E., Bartram, D., Gibb, D., Martin, J.H. CHAPTER 10 Emissions from Livestock and Manure Management. Report.
- Hegarty, R., et al., 2021. Evaluation of CH_4 inhibiting feed additives. Report.
- Hegarty, R., Passetti, R., Dittmer, K., Wang, Y., Shelton, S., Emmet-Booth, J., Wollenberg, E., McAllister, T., Leahy, S., Beauchemin, K., Gurwick,N., 2021. An evaluation of evidence for efficacy and applicability of CH_4 inhibiting feed additives for livestock. Report.
- Heijungs, R. and Huijbregts, M.A.J. (2004) A review of approaches to treat uncertainty in LCA. *Environmental Science & Technology*, 38(3), pp. 668–676.
- Henle, K., Alard, D., Clitherow, J., Cobb, P., Firbank, L., Kull, T., McCracken, D., Moritz, R.F.A., Niemelä, J. and Rebane, M. (2008) 'Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe – A review', *Agriculture, Ecosystems & Environment*, 124(1–2), pp.60–71.
- Hennessy, T., Kinsella, A., Moran, B., Quinlan, G., 2012. Teagasc National Farm Survey 2011. www.teagasc.ie.
- Henriksson, M., Flysjö, A., Cederberg, C., & Swensson, C. (2011). Variation in carbon footprint of milk due to management differences – analysis of 1051 Swedish dairy farms. Animal, 5(9), 1474–1484.
- Herron, J., et al., 2019. Whole farm modelling the effect of harvest date and fertiliser rate on emissions. Agricultural Systems 175, 66–78. doi:10.1016/J.AGSY.2019.05.013

- Herron, J., et al., 2021a. Simulated environmental impact of white clover in dairy systems. Journal of Dairy Science 104, 7902–7918. doi:10.3168/JDS.2020-19077
- Herron, J., et al., 2022. LCA of pasture-based dairy systems. J Dairy Sci 105, 5849–5869. https://doi.org/10.3168/jds.2021-21499
- Herron, J., O'Brien, D., Shalloo, L., 2022. LCA of pasture- based dairy production systems: Current and future performance. Jour- nal of Dairy Science 105, 5849–5869. URL: https://dx.doi.org/10. 3168/jds.2021-21499, doi:10.3168/jds.2021-21499.
- Honan, M., et al., 2021. Feed additives to reduce enteric CH_4. Animal Production Science 62, 1303–1317. https://dx.doi.org/10.1071/an20295
- Honan, M., Feng, X., Tricarico, J.M., Kebreab, E., 2021. Feed additives as a strategic approach to reduce enteric CH_4 production in cattle: modes of action, effectiveness and safety. Animal Production Science 62, 1303– 1317. URL: , doi:.
- Hoogstra, A.G. & Silvius, J. & De Olde, Evelien & Candel, Jeroen & Termeer, C.J.A.M. & Ittersum, Martin K. & Boer, I.J.M.. (2024). The transformative potential of circular agriculture initiatives in the North of the Netherlands. Agricultural Systems. 214. 103833. 10.1016/j.agsy.2023.103833.
- Hou, Y., Velthof, G.L. & Oenema, O., 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Global Change Biology, 21, pp.1293–1312. https://doi.org/10.1111/gcb.12767
- Hoxha, A., Christensen, B., 2018. The carbon footprint of fertiliser production URL: .
- Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E. et al. (2013) 'Mitigation of CH_4 and N_2O emissions from animal operations: I. A review of enteric CH_4 mitigation options', *Journal of Animal Science*, 91(11), pp.5045–5069.
- Hristov, A.N., Oh, J., Giallongo, F., Frederick, T.W., Harper, M.T. et al. (2015) 'An inhibitor persistently decreased enteric CH_4 emission from dairy cows with no negative effect on milk production', *Proceedings of the National Academy of Sciences*, 112(34), pp.10663–10668.
- Huijbregts, M.A.J., et al., 2017. ReCiPe2016 impact assessment method. Int J Life Cycle Assess 22, 138–147. https://dx.doi.org/10.1007/s11367-016-1246-y
- Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Van Zelm, R., 2017. Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of LCA 22, 138–147. URL: https://dx.doi.org/10.1007/s11367-016-1246-y, doi:10.1007/s11367-016-1246-y.
- "Husted, S., Husted, S., 1995. A simple model of ph in slurry. The Journal of Agricultural Science 124, 447–453. URL: https://www.cambridge. org/core/journals/journal-of-agricultural-science/article/

- simple-model-of-ph-in-slurry/1A75A1E1C202C7A3AB0EBFEA970E1E93, doi:10.1017/S0021859600073408."
- Hyde, B., Duffy, P., Ryan, A., Murphy, J., Fahey, D., Monaghan, S., MacFarlane, B., Kehoe., A., 2023. Ireland Informative Report 2023. Report.
- Hyde, B., et al., 2023. Ireland Informative Report 2023. Report.
- Hyland, J., Jones, D.L., Parkhill, K.A., Barnes, A.P. and Williams, A.P. (2016) 'Farmers' perceptions of climate change: identifying types', *Agricultural Systems*, 156, pp.64–74.
- Intergovernmental Panel on Climate Change (IPCC) (2019) *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*. Geneva: IPCC.
- Intergovernmental Panel on Climate Change, ., 2014. Climate change 2014:
- Intergovernmental Panel on Climate Change, ., 2019a. 2019 refinement to the 2006 ipcc guidelines for national GHG inventories, chapter 10 emissions from livestock and manure management .
- Intergovernmental Panel on Climate Change, ., 2019b. 2019 refinement to the 2006 ipcc guidelines for national GHG inventories, chapter 11 N_2O emissions from managed soils, and CO_2 emissions from lime and urea application .
- Intergovernmental Panel on Climate Change, ., 2023. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. Cambridge Uni- versity Press, Cambridge. pp. 923–1054. URL:
- Intergovernmental Panel on Climate Change, 2019a. 2019 refinement to 2006 IPCC guidelines. Chapter 10.
- Intergovernmental Panel on Climate Change, 2019b. 2019 refinement to 2006 IPCC guidelines. Chapter 11.
- International Dairy Federation (2010) *A common carbon footprint approach for dairy: The IDF guide to standard lifecycle assessment methodology for the dairy sector*. Brussels: IDF.
- International Dairy Federation (2015) *Guidance on Standardized Methodology for Carbon Footprint of Dairy Production and Processing*. Bulletin of the IDF No. 479/2015.
- International Dairy Federation (IDF) (2021) *Sustainable Dairy Partnership: Guidelines and Framework*. Brussels: IDF.
- International Dairy Federation (IDF) (2022) *IDF Position Paper on Enteric CH_4 Mitigation Strategies*. Brussels: IDF.
- ISO (ISO) (2006a) *ISO 14040: Environmental Management – LCA – Principles and Framework*. Geneva: ISO.
- ISO (ISO) (2006b) *ISO 14044: Environmental Management – LCA – Requirements and Guidelines*. Geneva: ISO.

- IPBES (2019) *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*. Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
- IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories. Intergovernmental Panel on Climate Change, Geneva.
- IPCC (2021) 'Climate Change 2021: The Physical Science Basis', Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- IPCC (2021) *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- IPCC (2021) *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
- IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- Irish Cattle Breeding Federation, ., 2020. A decade of dairy cow numbers 2011 to 2020. URL: .
- Irish Cattle Breeding Federation, 2020. A decade of dairy cow numbers 2011 to 2020. https://www.icbf.com/?p=17201.
- Irish Cattle Breeding Federation, 2021. Dairy cow population by county 2017 - 2021. https://www.icbf.com/?p=17810.
- ISO (2006) 'ISO 14044: Environmental management – LCA – Requirements and guidelines', ISO, Geneva.
- ISO (2006) Environmental management – LCA – Principles and framework (ISO 14044:2006). ISO, Geneva, Switzerland.
- ISO (2006b) *Environmental Management – LCA – Requirements and Guidelines (ISO 14044)*. Geneva: ISO.
- ISO, 2004. Environmental management - LCA - ISO 14040. https://www.iso.org/standard/37456.html
- ISO, 2004. Environmental management - LCA - principles and framework (iso 14040:2006). Environmental Management System Requirements 44. URL: .

- Iversen, S. V., Dalgaard, T., & Graversgaard, M. (2024). Discordance between farmers and scientists - Perspectives on nitrogen reduction measures in Denmark. Journal of environmental management, 352, 119877. https://doi.org/10.1016/j.jenvman.2023.119877
- Johnston, D.J., et al., 2020b. Performance and nutrient utilisation of dairy cows on red clover–perennial ryegrass silages. Irish Journal of Agricultural and Food Research 59. https://dx.doi.org/10.15212/ijafr-2020-0106
- Jones, Laurence & Provins, A & Holland, Mike & Mills, Gina & Hayes, Felicity & Emmett, B & Hall, J & Sheppard, Lucy & Smith, R & Sutton, M & Hicks, Kevin & Ashmore, Mike & Haines-Young, Roy & Harper-Simmonds, L. (2013). A review and application of the evidence for nitrogen impacts on ecosystem services. Ecosystem Services. 7. 10.1016/j.ecoser.2013.09.001. Harper-Simmonds, L., Holland, M., Mills, G. and Hayes, F. (2019) 'The impact of nitrogen deposition on ecosystem services and biodiversity in the UK', *Environmental Pollution*, 246, pp. 1–10.
- Kavanagh, I., Burchill, W., Healy, M.G., Fenton, O., Krol, D.J., Lanigan, G.J., 2019. Mitigation of NH_3 and GHG emissions from stored cattle slurry using acidifiers and chemical amendments. Journal of Cleaner Production 237. https://doi.org/10.1016/j.jclepro.2019.117822.
- Kavanagh, I., Fenton, O., Healy, M.G., Burchill, W., Lanigan, G.J., Krol, D.J., 2021. Mitigating NH_3 and GHG emissions from stored cattle slurry using agricultural waste, commercially available products and a chemical acidifier. Journal of Cleaner Production 294, 126251. https://doi.org/10.1016/j.jclepro.2021.126251.
- Kebreab, E., Bannink, A., Pressman, E.M., Walker, N., Karagiannis, A., van Gastelen, S., Dijkstra, J., 2023. A meta-analysis of effects of 3- nitrooxypropanol on CH_4 production, yield, and intensity in dairy cattle. J Dairy Sci 106, 927–936. doi:. 1525- 3198 Kebreab, Ermias Bannink, André Pressman, Eleanor May Walker, Nicola Karagiannis, Alexios van Gastelen, Sanne Dijkstra, Jan T32 GM136559/GM/NIGMS NIH HHS/United States Journal Article Meta- Analysis United States 2022/12/10 J Dairy Sci. 2023 Feb;106(2):927- 936. doi: 10.3168/jds.2022-22211. Epub 2022 Dec 7.
- Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P. and Tricarico, J.M. (2014) 'Enteric CH_4 in dairy cattle production: quantifying the opportunities and impact of reducing emissions', *Journal of Dairy Science*, 97(6), pp.3231–3261.
- Kupper, T., Häni, C., Neftel, A., Kincaid, C., Bühler, M., Amon, B. & VanderZaag, A., 2020. Ammonia and greenhouse gas emissions from slurry storage – A review. Agriculture, Ecosystems & Environment, 300, p.106963. https://doi.org/10.1016/j.agee.2020.106963
- Kristensen, T., Mogensen, L., Knudsen, M. T., & Hermansen, J. E. (2011). Effect of production system and farming strategy on GHG emissions from commercial dairy farms (LCA approach). Livestock Science, 140(1–3), 136–148.

- Krol, D.J., Carolan, R., Minet, E., McGeough, K.L., Watson, C.J., Forrestal, P.J., Lanigan, G.J., Richards, K.G., 2016. Improving and disaggre- gating N_2O emission factors for ruminant excreta on temperate pasture soils. Science of the Total Environment 568, 327–338. //dx.doi.org/10.1016/j.scitotenv.2016.06.0160048-9697/, doi:10.1016/j.scitotenv.2016.06.016."
- Kupper, T., Häni, C., Neftel, A., Kincaid, C., Bühler, M., Amon, B., VanderZaag, A., 2020. NH_3 and GHG emissions from slurry storage - a review. Agriculture, Ecosystems Environment 300, 106963. doi:10.1016/j.agee.2020.106963.
- Lahart, B., Costigan, H., Herron, J., Dwan, C., Kennedy, M., Egan, M., Shalloo, L., 2022. CH_4 mitigation strategies within pasture-based dairy systems. National Dairy Conference 2022 .
- Lanigan, G., Black, K., Donnellan, T., Crosson, P., Beausang, C., Hanrahan, K., Buckley, C., Lahart, B., Herron, J., Redmond, J., Shalloo, L., Krol, D., Forrestal, P., Farrelly, N., O'Brien, D., Lenehan, J., Hennessy, M., O'Donovan, M., Wall, D., O'Sullivan, L., O'Dwyer, T., Dineen, M., Waters, S., NiFlahartha, N., Houlihan, T., Murphy, P., Spink, J., Dillon, P., Upton, J., Richards, K., 2023. MACC 2023: An Updated Analysis of the GHG Abatement Potential of the Irish Agriculture and Land-Use Sectors between 2021 and 2030. Report.
- Lanigan, G., Donnellan, T., Hanrahan, K., Paul, C., Shalloo, L., Krol, D., Forrestal, P.J., Farrelly, N., O'Brien, D., ryan, M., Murphy, P., Caslin, B., Spink, J., Finnan, J., Boland, A., Upton, J., richards, K.G., 2019. An Analysis of Abatement Potential of GHG Emissions in Irish Agriculture 2021-2030. Report.
- Läpple, D., Sirr, G., 2019. Dairy intensification and quota abolition: A comparative study of production in ireland and the netherlands. EuroChoices 18, 26–32. URL: , doi:.
- Lassen, Jan & Løvendahl, Peter. (2016). Heritability estimates for enteric CH_4 emissions from Holstein cattle measured using noninvasive methods. Journal of Dairy Science. 99. 10.3168/jds.2015-10012.
- Ledgard, S. F., Falconer, S. J., Abercrombie, R., et al. (2020). Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. Journal of Dairy Science, 103(1), 1031–1046
- Lefcourt, A.M. & Meisinger, J.J., 2001. Effect of adding alum or zeolite to dairy slurry on ammonia volatilization and chemical composition. Journal of Dairy Science, 84(8), pp.1814–1821. https://doi.org/10.3168/jds.S0022-0302(01)74620-6
- Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., Simpson, D., Sutton, M.A., de Vries, W. and Weiss, F. (2015) Impacts of European livestock production: nitrogen, sulphur, phosphorus and GHG emissions, land-use, water eutrophication and biodiversity. *Environmental Research Letters*, 10(11), 115004.

- Leip, A., Weiss, F., Wassenaar, T., Domínguez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S., Biala, K., 2010. Evaluation of the Livestock Sector's Contribution to the EU GHG Emissions (GGELS) – Final Report.
- Li, Xixi & Norman, Hayley & Kinley, Robert & Laurence, Michael & Wilmot, Matt & Bender, Hannah & de Nys, Rocky & Tomkins, Nigel. (2016). Asparagopsis taxiformis decreases enteric CH_4 production from sheep. Animal Production Science. 58. 681-688. 10.1071/AN15883.
- Lichiheb, N., et al., 2019. Urease inhibitor effect on NH_3 emissions following urea-based fertiliser application. Agricultural and Forest Meteorology 269-270, 78–87. https://doi.org/10.1016/j.agrformet.2019.02.005.
- Litrico, I. and Violle, C. (2015) 'Diversity in plant breeding: a new conceptual framework', *Trends in Plant Science*, 20(10), pp.604–613.
- Llonch, P., Somarriba, M., Duthie, C. A., Troy, S., Roehe, R., Rooke, J., Haskell, M. J., & Turner, S. P. (2018). Temperament and dominance relate to feeding behaviour and activity in beef cattle: implications for performance and CH_4 emissions. Animal : an international journal of animal bioscience, 12(12), 2639–2648. https://doi.org/10.1017/S1751731118000617
- Lugato, E., Leip, A., Jones, A., 2018. Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. Nature Cli- mate Change 8. doi:.
- Manmohan, C., et al., 2023a. Green technology and environmental sustainability in tourism: A bibliometric analysis. E3S Web Conf. 391, 01179. https://doi.org/10.1051/e3sconf/202339101179
- Markiewicz-Keszycka, M., Carter, A., O'Brien, D., Henchion, M., Mooney, S., Hynds, P., 2022. Renewable agriculture and food systems pro- environmental diversification of pasture-based dairy and beef production in ireland, the united kingdom and new zealand: a scoping review of impacts and challenges. Renewable Agriculture and Food Systems 38. doi:.
- Martin, C., Morgavi, D.P. and Doreau, M. (2010) 'CH_4 mitigation in ruminants: from microbe to the farm scale', *Animal*, 4(3), pp.351–365.
- McAuliffe, G. A., Takahashi, T., Beal, T., Huppertz, T., Leroy, F., Buttriss, J., Collins, A. L., Drewnowski, A., McLaren, S. J., Ortenzi, F., van der Pols, J. C., van Vliet, S., & Lee, M. R. F. (2023). Protein quality as a complementary functional unit in LCA. The international journal of LCA, 28(2), 146–155.
- "Melgar, A., Harper, M.T., Oh, J., Giallongo, F., Young, M.E., Ott, T.L., Duval, S., Hristov, A.N., 2020. Effects of 3-nitrooxypropanol on rumen fermentation, lactational performance, and resumption of ovarian cyclic- ity in dairy cows. J Dairy Sci 103, 410–432. doi:10.3168/jds.2019-17085. 1525-3198 Melgar, A Harper, M T Oh, J Giallongo, F Young, M E Ott, T L Duval, S Hristov, A N Journal

Article Randomized Controlled Trial, Veterinary United States 2019/11/18 J Dairy Sci. 2020 Jan;103(1):410-432. doi: 10.3168/jds.2019-17085. Epub 2019 Nov 14."

- Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.C., Vågen, T.G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. URL: , doi:https://doi.org/10.1016/j.geoderma.2017.01.002.
- Ministry for the Environment (2022) *Pricing Agricultural Emissions: Consultation Document*. New Zealand Government.
- Miranda, C., Soares, A.S., Coelho, A.C., Trindade, H., Teixeira, C.A., 2021. Environmental implications of stored cattle slurry treatment with sulphuric acid and biochar: A LCA approach. Environmental Research 194, 110640. URL: , doi:https://doi.org/10.1016/j.envres.2020.110640.
- "Misselbrook, T., Gilhespy, S., 2020. Inventory of NH_3 emissions from uk agriculture 2018 URL: https://naei.beis.gov.uk/reports/reports? report_id=998."
- Misselbrook, T.H., 2015. Inventory of NH_3 emissions from UK agriculture.
- Misselbrook, T.H., Smith, K.A., Johnson, R.A. and Pain, B.F. (2005) 'Slurry application techniques to reduce NH_3 emissions: Results of some UK field-scale experiments', *Biosystems Engineering*, 91(4), pp.471–480.
- Misselbrook, T., Hunt, J., Perazzolo, F. & Provolo, G., 2016. Greenhouse gas and ammonia emissions from slurry storage: Impacts of temperature and potential mitigation through covering (pig slurry) or acidification (cattle slurry). Journal of Environmental Quality, 45, pp.1520–1530. https://doi.org/10.2134/jeq2015.12.0618
- Mockler, Eva & Bruen, Michael. (2018). Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures.
- Moloney, T., Sheridan, H., Grant, J., O'Riordan, E.G., O'Kiely, P., 2021. Yield of binary-and multi-species swards relative to single-species swards in intensive silage systems doi:10.2478/ijafr-2020-0002.
- Montes F, Meinen R, Dell C, Rotz A, Hristov AN, Oh J, Waghorn G, Gerber PJ, Henderson B, Makkar HP, Dijkstra J. Special topics--Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. J Anim Sci. 2013 Nov;91(11):5070-94. doi: 10.2527/jas.2013-6584. Epub 2013 Sep 17. PMID: 24045493.

- Moscovici Joubran, A., Pierce, K. M., Garvey, N., Shalloo, L., & O'Callaghan, T. F. (2021). Invited review: A 2020 perspective on pasture-based dairy systems and products. Journal of dairy science, 104(7), 7364–7382. https://doi.org/10.3168/jds.2020-19776
- Moure Abelenda, A., 2021. Highlighting the importance of the chemical amendments to tackle GHG (GHG) emissions from manure and slurry. doi:10.13140/RG.2.2.13612.74886.
- Mytton, L., Cresswell, A., Colbourn, P., 2006. Improvement in soil structure associated with white clover. Grass and Forage Science 48, 84–90. doi:.
- Naranjo, A. M., Sieverding, H., Clay, D., & Kebreab, E. (2023). Carbon footprint of South Dakota dairy production system and assessment of mitigation options. PloS one, 18(3), e0269076. https://doi.org/10.1371/journal.pone.0269076
- Nemecek, T., Jungbluth, N., i Canals, L.M. and Schenck, R. (2011) 'Environmental impacts of food consumption and nutrition: where are we and what is next?', *International Journal of LCA*, 16(7), pp.607–620.
- Nguyen, T.L.T., Hermansen, J.E. and Mogensen, L. (2010) 'Environmental consequences of different beef production systems in the EU', *Journal of Cleaner Production*, 18(8), pp.756–766.
- Nolan, A., Brennan, R.B., Healy, M.G. & Fenton, O., 2023. Scale-up of a peroxide-based pig slurry additive for gaseous emission reduction and downstream value retention. Cleaner Waste Systems, 4, 100051. https://doi.org/10.1016/j.clwas.2023.100051
- Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E. and Sonesson, U. (2017) 'The role of LCA in supporting sustainable agri-food systems: A review of the challenges', *Journal of Cleaner Production*, 140, pp.399–409.
- Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V. and Sala, S. (2017) 'Environmental impacts of food consumption in Europe', *Journal of Cleaner Production*, 140, pp.753–765.
- "Nyfeler, D., Huguenin-Elie, O., Suter, M., Frossard, E., Connolly, J.,
- Lüscher, A., 2009. Strong mixture effects among four species in fertil- ized agricultural grassland led to persistent and consistent transgressive overyielding. Journal of Applied Ecology 46, 683–691. doi:10.1111/J. 1365-2664.2009.01653.X."
- O’Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C. and Wallace, M., 2012. A LCA of seasonal grass-based and confinement dairy farms. Agricultural Systems, 107, pp.33–46.
- O’Brien, D., Brennan, P., Humphreys, J., Ruane, E., Shalloo, L., 2014. An appraisal of carbon footprint of milk from commercial grass- based dairy farms in ireland according to a certified life cycle assess- ment methodology. International Journal of LCA 19, 1469–1481. URL: , doi:.

- O’Brien, D., et al., 2014. A case study of the carbon footprint of milk. Journal of Dairy Science 97, 1835–1851. https://www.sciencedirect.com/science/article/pii/S0022030214000319
- O’Brien, D., Hennessy, T., Moran, B. and Shalloo, L. (2014) 'Relating the carbon footprint of milk from Irish dairy farms to economic performance', *Journal of Dairy Science*, 97(12), pp. 7562–7574.
- O’Brien, D., Horan, B., Berry, D.P. and Shalloo, L. (2014) 'The influence of strain of Holstein-Friesian cow and feeding system on GHG emissions from pastoral dairy farms', *Journal of Dairy Science*, 97(12), pp. 7663–7679.
- O’Brien, D., Upton, J., Ryan, M. and Shalloo, L. (2016) 'A LCA of the effect of intensification on the environmental impacts and resource use of grass-based dairy farming', *Agricultural Systems*, 144, pp.122–133.
- O’Rourke, E. and Finn, J.A. (2022) 'Agro-ecological approaches to enhancing farmland biodiversity in Ireland', *Frontiers in Sustainable Food Systems*, 6, 831264.
- Opoku, Daniel & Healy, Mark & Fenton, Owen & Daly, Kheireddine & Condon, Tomas & Tuohy, Pat. (2024). An integrated connectivity risk ranking for phosphorus and nitrogen along agricultural open ditches to inform targeted and specific mitigation management. Frontiers in Environmental Science. 12. 10.3389/fenvs.2024.1337857.
- Overmeyer, V., Trimborn, M., Clemens, J., Hölscher, R. & Büscher, W., 2023. Acidification of slurry to reduce ammonia and methane emissions: Deployment of a retrofittable system in fattening pig barns. Journal of Environmental Management, 331, p.117263. https://doi.org/10.1016/j.jenvman.2023.117263
- Owusu-Twum, M.Y., Kelleghan, D., Gleasure, G., et al., 2024. Mitigation of ammonia and methane emissions with manure amendments during storage of cattle slurry. Waste Management & Research, 43(4), pp.568–579. https://doi.org/10.1177/0734242X241265007
- Parajuli, Ranjan & Dalgaard, T. & Jørgensen, Uffe & Adamsen, Anders & Knudsen, Marie & Birkved, Morten & Gylling, Morten & Schjørring, Jan. (2015). Biorefining in the prevailing energy and materials crisis: A review of sustainable pathways for biorefinery value chains and sustainability assessment methodologies. Renewable and Sustainable Energy Reviews. 43. 244-263. 10.1016/j.rser.2014.11.041.
- Pe’er, G., Dicks, L.V., Visconti, P., Arlettaz, R., Báldi, A. et al. (2014) 'EU agricultural reform fails on biodiversity', *Science*, 344(6188), pp.1090–1092.
- Penati, C.A., Tamburini, A., Bava, L., Zucali, M. and Sandrucci, A., 2013. Environmental impact of cow milk production in the central Italian Alps using LCA. Italian Journal of Animal Science, 12(4), pp.e96–e96.

- Petersen SO, Blanchard M, Chadwick D, Del Prado A, Edouard N, Mosquera J, Sommer SG. Manure management for greenhouse gas mitigation. Animal. 2013 Jun;7 Suppl 2:266-82. doi: 10.1017/S1751731113000736. PMID: 23739469.
- Peterson, C., Mitloehner, F., 2021. Sustainability of the dairy industry: Emissions and mitigation opportunities. Frontiers in Animal Science 2. doi:.
- Pijlman, J., et al., 2018. Effect of feeding the grass fibrous fraction from biorefinery. Report.
- Pinares-Patiño, C.S., Hickey, S.M., Young, E.A., Dodds, K.G., MacLean, S. et al. (2013) 'Heritability estimates of CH_4 emissions from sheep', *Animal*, 7(s2), pp.316–321.
- Pirhofer-Walzl, K., Rasmussen, J., Høgh-Jensen, H., Eriksen, J., Søegaard, K., Rasmussen, J., 2012. Nitrogen transfer from forage legumes to nine neighbouring plants in a multi-species grassland. Plant and Soil 350, 71–84. URL: s11104-011-0882-z, doi:.
- Plantureux, S., et al., 2014. An indicator-based tool to assess impacts of multi-specific swards.
- Poore, J. and Nemecek, T. (2018) 'Reducing food's environmental impacts through producers and consumers', *Science*, 360(6392), pp.987–992.
- Ravenni, G., et al., 2023. Integration of a drying and pyrolysis system in a green biorefinery. Biomass Conversion and Biorefinery.
- Ravindran, R., et al., 2021. Production of green biorefinery protein concentrate for pigs. Clean Technologies 3, 656–669. https://dx.doi.org/10.3390/cleantechnol3030039
- Ravindran, R., et al., 2022. Biogas, bioCH_4 and digestate potential from green biorefineries. Clean Technologies 4, 35–50. https://dx.doi.org/10.3390/cleantechnol4010003
- Regueiro, I., Coutinho, J., Gioelli, F., Balsari, P., Dinuccio, E. & Fangueiro, D., 2016. Acidification of raw and co-digested pig slurries with alum before mechanical separation reduces gaseous emission during storage of solid and liquid fractions. Agriculture, Ecosystems & Environment, 227, pp.42–51. https://doi.org/10.1016/j.agee.2016.04.016
- Reisinger, A., Clark, H., Abercrombie, R., Aspin, M., Harris, M., Ettema, P., Hoggard, A., Newman, M.,& Sneath, G. (2018). Future options to reduce biological GHG emissions on-farm: Critical assumptions and national-scale impact [Report to the Biological Emissions Reference Group].
- Reisinger, Andy & Ledgard, Stewart & Falconer, Shelley. (2017). Sensitivity of the carbon footprint of New Zealand milk to GHG metrics. Ecological Indicators. 81. 74-82. 10.1016/j.ecolind.2017.04.026.
- Rencricca, G., Froldi, F., Moschini, M., Trevisan, M., & Lamastra, L. (2023). Mitigation action scenarios applied to dairy farm management systems. Foods, 12(9), 1860

- RIVM (2020) Informative Inventory Report 2020: Emissions of substances to air in the Netherlands. Bilthoven: National Institute for Public Health and the Environment (RIVM). Available at: https://www.rivm.nl/bibliotheek/rapporten/2020-0032.pdf
- Roca-Fernández, A.I., Peyraud, J.L., Delaby, L., Delagarde, R., 2016. Pasture intake and milk production of dairy cows rotationally graz- ing on multi-species swards. Animal 10, 1448–1456. doi: .
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S. et al. (2009) 'A safe operating space for humanity', *Nature*, 461(7263), pp.472–475.
- Rogelj, J. and Schleussner, C.F. (2019) Unintentional unfairness when applying new GHG emissions metrics at country level. *Environmental Research Letters*, 14(11), 114039.
- Romero-Perez, A., Okine, E.K., McGinn, S.M., Guan, L.L., Oba, M.,Duval, S.M., Kindermann, M., Beauchemin, K.A., 2015. Sus- tained reduction in CH_4 production from long-term addition of 3-nitrooxypropanol to a beef cattle diet1. Journal of Animal Science 93, 1780–1791.
- Röös, E., Sundberg, C. and Hansson, P.-A. (2011) 'Uncertainties in the carbon footprint of food products: a case study on meal alternatives in Sweden', *Environmental Science & Policy*, 14(5), pp.562–575.
- Roque, B. M., Venegas, M., Kinley, R. D., de Nys, R., Duarte, T. L., Yang, X., & Kebreab, E. (2021). Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric CH_4 by over 80 percent in beef steers. PloS one, 16(3), e0247820. https://doi.org/10.1371/journal.pone.0247820
- Rotz, C.A., Montes, F. and Chianese, D.S. (2010) 'The carbon footprint of dairy production systems through partial LCA', *Journal of Dairy Science*, 93(3), pp.1266–1282.
- Rubhara, T., Gaffey, J., Hunt, G., Murphy, F., O'Connor, K., Buckley, E., Vergara, L.A., 2024. A business case for climate neutrality in pasture- based dairy production systems in ireland: Evidence from farm zero c. Sustainability 16, 1028. URL: 1028.
- Sanes, J.R., 2019. Tell me a story. eLife 8. https://doi.org/10.7554/elife.50527.
- Santamaría-Fernández, M., et al., 2018. Demonstration-scale protein recovery from grass clover. Biofuels 13.
- Saunders, M., Krol, D., Lanigan, G.J., Forristal, P.J., Richards, K.G. and Watson, C.J. (2016) 'Inter-annual variation in N_2O emissions from Irish grasslands with contrasting soil drainage and management', *Agriculture, Ecosystems & Environment*, 222, pp.185–195.
- Schulte, R.P.O., et al. (2021) 'Agroecosystem resilience to climate change: Concepts and assessments', Journal of Environmental Management, 295, 113091.
- SEAI (2022) Energy in Ireland 2022 Report. Sustainable Energy Authority of Ireland, Dublin.
- Serra, E., et al., 2021. Comparing green biorefinery press cake for cows.

- Serra, E., et al., 2023. Biorefined press cake silage as feed source for dairy cows. Livestock Science 267, 105135. https://www.sciencedirect.com/science/article/pii/S1871141322003080
- Sha, Z., Lv, T., Staal, M., Ma, X., Wen, Z., Li, Q., Pasda, G., Misselbrook, T., Liu, X., 2020. Effect of combining urea fertiliser with p and k fertilizers on the efficacy of urease inhibitors under different storage conditions. Journal of Soils and Sediments 20. doi:.
- Sheridan, Helen & McMahon, Barry & Carnus, Tim & Finn, John & Anderson, Annette & Helden, Alvin & Kinsella, Anne & Purvis, Gordon. (2011). Pastoral farmland habitat diversity in South-East Ireland. Agriculture Ecosystems & Environment. 144. 130-135. 10.1016/j.agee.2011.07.011.
- Smith, P.E., Kelly, A.K., Kenny, D.A., Waters, S.M., 2022. Enteric CH_4 research and mitigation strategies for pastoral-based beef cattle production systems. Frontiers in Veterinary Science 9. URL: , doi: .
- Soder, K.J., Brito, A.F., 2023. Enteric CH_4 emissions in grazing dairy systems* *presented as part of the joint adsa midwest branch/forages and pastures symposium: Grazing to improve profitability of midwest dairy farms held at the adsa annual meeting, june 2022. JDS Communications 4, 324–328. URL: , doi:https://doi.org/10.3168/jdsc.2022-0297.
- Sokolov, V., Habtewold, J., VanderZaag, A., Dunfield, K., Gregorich, E., Wagner-Riddle, C., Venkiteswaran, J.J. & Gordon, R., 2021. Response curves for ammonia and methane emissions from stored liquid manure receiving low rates of sulfuric acid. Frontiers in Sustainable Food Systems, 5, Article 678992. https://doi.org/10.3389/fsufs.2021.678992
- Sommer, S.G. & Hutchings, Nicholas. (2001). Review: NH_3 emissions from field applied manure and its reduction. Eur. J Agron.. 15. 1-55.
- Stokstad E. (2019). Nitrogen crisis threatens Dutch environment-and economy. Science (New York, N.Y.), 366(6470), 1180–1181. https://doi.org/10.1126/science.366.6470.1180
- Styles, D., Gibbons, J., Williams, A. P., Dauber, J., Stichnothe, H., Urban, B., Chadwick, D. R., & Jones, D. L. (2015). Consequential LCA of biogas, biofuel and biomass energyoptions within an arable crop rotation. GCB Bioenergy, 7(6), 1305-1320.https://doi.org/10.1111/gcbb.12246
- Styles, D., Gonzalez-Mejia, A., Moorby, J., Foskolos, A. and Gibbons, J. (2018) 'Mitigation of carbon footprint and NH_3 emission from livestock production systems: a meta-analysis', *Global Change Biology*, 24(2), pp.709–722.
- Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H. and Grizzetti, B. (2011) *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*. Cambridge: Cambridge University Press.
- Takkellapati, S., et al., 2018. Overview of biorefinery-derived platform chemicals. Clean Technologies and Environmental Policy 20, 1615–1630. https://dx.doi.org/10.1007/s10098-018-1568-5

- Teagasc (2021) *Fertiliser Use Survey 2020*. Carlow: Teagasc.
- Teagasc (2022) *Agricultural GHG Research and Mitigation in Ireland*. Carlow: Teagasc.
- Teagasc (2022) *National Farm Survey Sustainability Report 2021*. Carlow: Teagasc.
- Teagasc (2022) National Fodder and Feed Security Report. Teagasc, Ireland.
- Teagasc (2023) 'National Farm Survey Sustainability Report 2023', Teagasc, Oak Park.
- Teagasc (2023) *Fertiliser Use Survey 2022*. Carlow: Teagasc.
- Teillard, F., Anton, A., Dumont, B., Finn, J.A., Henry, B., Souza, D.M., Manzano P., Milà i Canals, L., Phelps, C., Said, M., Vijn, S., White, S. (2016). A review of indicators and methods to assess biodiversity – Application to livestock production at global scale. Livestock Environmental Assessment and Performance (LEAP) Partnership. FAO, Rome, Italy.
- Thoma, G., Popp, J., Nutter, D., Shonnard, D., Ulrich, R., Matlock, M., Kim, D.S., Neiderman, Z., Kemper, N., East, C., Adom, F., 2013. GHG emissions from milk production and consumption in the united states: A cradle-to-grave LCA circa 2008. International Dairy Journal 31. doi:.
- Thoma, Gregory & Jolliet, Olivier & Wang, Ying. (2013). A biophysical approach to allocation of life cycle environmental burdens for fluid milk supply chain analysis. International Dairy Journal. 31. S41-S49. 10.1016/j.idairyj.2012.08.012.
- Thorn, C.E., Nolan, S., Lee, C.S., Friel, R. and O'Flaherty, V., 2022. Novel slurry additive reduces gaseous emissions during storage thereby improving renewable energy and fertiliser potential. Journal of Cleaner Production, 358, p.132004. https://doi.org/10.1016/j.jclepro.2022.132004
- Turna, F. (2025). Taxation of agricultural emissions in combating climate change: The case of Denmark. JOURNAL OF LIFE ECONOMICS, 12(1), e2713. https://doi.org/10.15637/jlecon.2713
- Uddin, M.E., Tricarico, J.M., Kebreab, E., 2022. Impact of nitrate and 3- nitrooxypropanol on the carbon footprints of milk from cattle produced in confined-feeding systems across regions in the united states: A life cycle analysis. Journal of Dairy Science doi:.
- UNECE (2021) Ammonia Emissions from Livestock: A Major Challenge for Air Quality. United Nations Economic Commission for Europe. Available at: https://unece.org/
- UNEP-SETAC (2011) Global Guidance Principles for LCA Databases: A Basis for Greener Processes and Products. United Nations Environment Programme – Society of Environmental Toxicology and Chemistry.
- Ungerfeld, E.M., 2022. Opportunities and hurdles to the adoption and enhanced efficacy of feed additives towards pronounced mitigation of enteric CH_4 emissions from ruminant livestock. CH_4 1, 262– 285. URL: . Van Gastelen, S., Dijkstra, J., Heck, J.M.L., Kindermann, M., Klop, A., de Mol, R., Rijnders, D., Walker, N., Bannink, A., 2022. CH_4 mitigation potential of 3-nitrooxypropanol in

lactating cows is influ- enced by basal diet composition. Journal of Dairy Science URL: //doi.org/10.3168/jds.2021-20782, doi:.

- van der Werf, H.M.G., Knudsen, M.T. and Cederberg, C. (2020) 'Towards better representation of organic agriculture in LCA', *Nature Sustainability*, 3(6), pp.419–425.
- Van Gastelen, S., Dijkstra, J., Heck, J.M.L., Kindermann, M., Klop, A.,de Mol, R., Rijnders, D., Walker, N., Bannink, A., 2022. CH_4 mitigation potential of 3-nitrooxypropanol in lactating cows is influ- enced by basal diet composition. Journal of Dairy Science URL:
- van Grinsven, H.J.M., Erisman, J.W., de Vries, W. and Westhoek, H. (2015) Potential of extensification of European agriculture for a more sustainable food system, focusing on nitrogen. *Environmental Research Letters*, 10(2), 025002.
- van Middelaar, C.E., Dijkstra, J., Berentsen, P.B.M. and de Boer, I.J.M. (2014) 'Cost-effectiveness of feeding strategies to reduce GHG emissions from dairy farming', *Journal of Dairy Science*, 97(4), pp.2427–2439.
- van Zanten, H.H.E., Herrero, M., van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C. and de Boer, I.J.M. (2018) Defining a land boundary for sustainable livestock consumption. *Global Change Biology*, 24(9), pp. 4185–4194.
- Vellinga, T.V., Vries, M.d., 2018. Effectiveness of climate change mitigation options considering the amount of meat produced in dairy systems. Agricultural Systems 162, 136–144. URL:
- Velthof, G.L., Oudendag, D., Witzke, H.P., Asman, W.A.H., Klimont, Z. and Oenema, O. (2009), Integrated Assessment of Nitrogen Losses from Agriculture in EU-27 using MITERRA-EUROPE. J. Environ. Qual., 38: 402-417. https://doi.org/10.2134/jeq2008.0108
- Wall, D.P., Jordan, P., Melland, A.R., Mellander, P.E., Buckley, C., Reaney, S.M. and Shortle, G. (2011) 'Using the nutrient transfer continuum concept to evaluate the European Union Nitrates Directive National Action Programme', *Environmental Science & Policy*, 14(6), pp.664–674.
- Wanapat, M., Prachumchai, R., Dagaew, G., Matra, M., Phupaboon, S., Sommai, S., Suriyapha, C., 2024. Potential use of seaweed as a dietary supplement to mitigate enteric CH_4 emission in ruminants. Science of The Total Environment 931, 173015. URL: , doi:https://doi.org/10.1016/j.scitotenv.2024.173015.
- Wang, Y., et al., 2023. Responses of CH_4, N_2O, and NH_3 emissions to different slurry pH values. Environmental Research 234, 116613. doi:10.1016/j.envres.2023.116613.
- Wang, S, Ang, F & Oude Lansink, A 2023, 'Mitigating GHG emissions on Dutch dairy farms. An efficiency analysis incorporating the circularity principle.', Agricultural Economics (United Kingdom), vol. 54, no. 6, pp. 819-837. https://doi.org/10.1111/agec.12804

- Wang, Y., Xu, W., Cong, Q., Wang, Y., Wang, W., Zhang, W., Zhu, Z., Dong, H., 2023. Responses of ch(4), n(2)o, and nh(3) emissions to different slurry ph values of 5.5-10.0: Characteristics and mechanisms. Environ Res 234, 116613. doi:. 1096- 0953 Wang, Yue Xu, Wenqian Cong, Qunxin Wang, Youxu Wang, Wenzan Zhang, Wanqin Zhu, Zhiping Dong, Hongmin Journal Article Research Support, Non-U.S. Gov't Netherlands 2023/07/13 Environ Res. 2023 Oct 1;234:116613. doi: 10.1016/j.envres.2023.116613. Epub 2023 Jul 10.
- Waters, S., 2023. Development and evaluation of feed additives to reduce enteric CH_4 emissions. Report.
- Weidema, B.P., Thrane, M., Christensen, P., Schmidt, J. and Løkke, S. (2009) 'Carbon footprint: a catalyst for LCA?', *Journal of Industrial Ecology*, 12(1), pp.3–6.
- Weiler, V., Udo, H.M.J., Viets, T.C., Crane, T.A. and de Boer, I.J.M. (2014) 'Handling multi-functionality of livestock in a LCA: The case of smallholder dairying in Kenya', *Current Opinion in Environmental Sustainability*, 8, pp.29–38.
- Weiss, F., Leip, A., 2012. GHG emissions from the eu livestock sector: A LCA carried out with the capri model. Agri- culture, Ecosystems and Environment 149, 124–134. URL: , doi: .
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. and Weidema, B.P. (2016) The ecoinvent database version 3 (part I): overview and methodology. *International Journal of LCA*, 21(9), pp. 1218–1230.
- Wilfart, Aurélie & Prudhomme, Jehane & Jean-paul, Blancheton & Aubin, Joël. (2013). LCA and emergy accounting of aquaculture systems: Towards ecological intensification. Journal of environmental management. 121C. 96-109. 10.1016/j.jenvman.2013.01.031.
- Williams, J., Chambers, B., Thorman, R., Sagoo, L., Chadwick, D. R. and Misselbrook, T. H. 2013. The importance of direct and indirect N_2O emissions from contrasting cattle slurry application timings. Abstracts GHG and Animal Agriculture (GGAA) Conference, Dublin, 23-26 June 2013 .
- Yan, M.J., Humphreys, J. and Holden, N.M. (2013) 'An evaluation of LCA of European milk production', *Journal of Environmental Management*, 126, pp.109–120.
- Zampori, L. and Pant, R. (2019) Suggestions for updating the Product Environmental Footprint (PEF) method. EUR 29682 EN, Publications Office of the European Union, Luxembourg.
- Zeeman, G., Gerbens, S., 2002. CH_4 emissions from animal manure. In: Background Papers IPCC Expert Meetings on Good Practice Guidance and Uncertainty Management in National GHG Invento-ries. / IPCC National GHG Inventories Programme (IPCC- NGGIP). - [S.l.] : [s.n.], 2002 .
- Zehetmeier, M., Baudracco, J., Hoffmann, H. and Heißenhuber, A. (2014) 'Does increasing milk yield per cow reduce GHG emissions? A system approach for holistic sustainability assessment', *Animal*, 8(10), pp.1698–1708.