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Evaluating circular practices in agriculture: A farm-level nitrogen and greenhouse gas marginal abatement cost curve approach

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ABSTRACT

Adoption of more circular farming systems that prioritise renewable and recycled resources could enhance nutrient cycling, reduce farm costs and lower greenhouse gas (GHG) emissions by decreasing reliance on external inputs. This study is the first to incorporate nitrogen (N) efficiency into a marginal abatement cost curve framework, bridging GHG mitigation with nutrient management. This integrated approach provides new insights into circular practices that can deliver win–win benefits and help avoid trade-offs between two of agriculture's most pressing environmental challenges. Using regional farm data and mass flow models, we investigated eight circular practices across five representative UK farming systems. Alternative feed ingredients reduced GHG emissions by 4.7% and saved £200 Mg CO_2e^{-1} yr^{-1} for the mixed farm. Solid-liquid slurry separation was the most cost-effective and N efficient practice for the dairy farm, reducing emissions by 4.8%, saving £129 Mg CO_2e^{-1} yr^{-1} and reducing the N balance by 17 kg N Mg CO_2e^{-1} yr^{-1}. Cover crops and multispecies leys were optimal for cost-effective and N-efficient emission reductions on arable and beef-sheep farms. While anaerobic digestion reduced emissions and improved N efficiency, it was not cost-effective. System-based practices, such as mixed crop-livestock integration, showed greater regional than individual farm-level mitigation potential. Future research could explore regional-scale and broader environmental, economic and social impacts of circular practices to better inform policy and increase their appeal. Our results reveal farm-specific strategies that deliver multiple, cost-effective environmental benefits, highlighting the value of linking climate and nutrient management in sustainable agriculture.

1. Introduction

The UK government has legislated a net zero greenhouse gas (GHG) emissions target by 2050. Achieving this goal will require significant mitigation efforts from many sectors, including agriculture. Agriculture accounted for 12% of total UK GHG emissions in 2022, with the main sources being emissions of methane (CH_4) from enteric fermentation within ruminant livestock, and nitrous oxide (N_2O) from soils following application of fertiliser and manure and livestock excreta deposited whilst grazing (DESNZ, 2024a). Achieving net zero will necessitate substantial emission reductions from agriculture, especially within livestock systems, as highlighted by Hyland et al. (2016b) and reaffirmed by McNicol et al. (2024).

Many mitigation options offer 'win-win' solutions, reducing GHG emissions while enhancing farm profitability and resilience (Moran et al., 2013). However, cost-effectiveness varies across farms and regions, leading to uneven adoption (Fellmann et al., 2021). Focusing only on the cost-effectiveness of mitigation options means other measures can be overlooked, slowing GHG reduction efforts and requiring policy incentives that may divert resources from more efficient strategies. These overlooked measures may align with other farmer priorities—such as cost savings, improved nutrient management or emissions reduction—that improve uptake (Fellmann et al., 2021). Farmers focused on profitability may prefer low-cost options, while those prioritising nutrient use efficiency (e.g. fertiliser, feed and manure management) may adopt nitrogen (N)-efficient practices, even when there may be higher upfront costs. Integrating cost-effectiveness and nutrient management could broaden the appeal of mitigation strategies.

The first UK-wide attempt to develop an economically efficient GHG

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Nomenclature

3Rs	Reduce, Reuse/Recycle and Regenerate
AD	Anaerobic digestion
CE	Circular economy
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CP	Crude protein
FBS	Farm Business Survey
GHG	Greenhouse gas
GWP_{100}	Global Warming Potential over 100 years
kg CO_2e kg^{-1} CP output yr^{-1}	Kilograms of carbon dioxide equivalent emitted per kilogram of crude protein output per year
kg CO_2e ha^{-1} yr^{-1}	Kilograms of carbon dioxide equivalent emitted per hectare of land per year
kg N yr^{-1}	Kilograms of nitrogen per year
LCA	Life Cycle Assessment
MACC	Marginal abatement cost curve
Mg	Megagram; equivalent to 1,000 kilograms (1 metric tonne)
Mg CO_2e yr^{-1}	Megagrams of carbon dioxide equivalent emitted per year
N	Nitrogen
NH_3	Ammonia
N_2O	Nitrous oxide
NUTS	Nomenclature of Territorial Units for Statistics
NVZ	Nitrate Vulnerable Zone
P	Phosphorus

emissions budget for agriculture was by Moran et al. (2011), who produced a 'bottom-up' marginal abatement cost curve (MACC) detailing the costs of crop, soil and livestock measures against a 'business as usual' baseline. Their work demonstrated the value of MACCs in reflecting variability across farming systems and the need for farm type- and region-specific approaches—a principle adopted in this study. Eory et al. (2015) quantified the abatement potential and cost effectiveness of 24 measures in a UK-wide MACC, while Eory et al. (2020) assessed 21 practices in Scotland. Barnes et al. (2022) extended the analysis to 36 measures for English farming and incorporated a qualitative assessment of wider environmental and social impacts. However, important gaps remain. These studies have mainly focused on national cost-effectiveness assessments, overlooking farm-level diversity and nutrient management—both closely linked to emissions—and have not systematically assessed circular farming practices, which offer distinct opportunities for recycling resources and reducing reliance on external inputs.

There has been increasing emphasis on transitioning towards circular farming systems (Grumbine et al., 2021), which apply circular economy (CE) principles to agriculture (Ellen MacArthur Foundation, 2021). The CE framework, centred on the '3Rs'—Reduce, Reuse/Recycle and Regenerate—offers a strategy to reduce GHG emissions, enhance nutrient cycling, and strengthen resilience in food systems (Velasco-Muñoz et al., 2021). Circular farming practices aim to reduce reliance on fossil fuel-derived inputs, reuse or recycle resources within and beyond the farm, and regenerate surrounding natural systems (Velasco-Muñoz et al., 2021). Examples include substituting synthetic fertilisers with livestock manure or legume cover crops, replacing imported soya-based feed with home-grown feed or by-products, and employing strategies and technologies that maximise the value of such resources, such as sharing resources and integrating crop-livestock systems, as well as solid–liquid slurry separation, anaerobic digestion and composting of manure. These practices form the operational foundation of circular farming systems (de Boer and van Ittersum, 2018).

The variety of livestock and mixed systems in the UK provide a good case study for exploring the application of circular practices. The systems vary in stocking density and management intensity, influenced by soil type, slope, climate, elevation, forage availability and local socio-economic conditions. As a result, their potential to adopt circular practices and reduce GHG emissions differs. Evans et al. (2025) explored farmer behaviours in relation to the adoption of emerging circular practices, including the eight assessed in this study: solid-liquid slurry separation, composting farmyard manure, anaerobic digestion (AD) of slurry and farmyard manure, application of recycled biosolids, use of alternative feed ingredients, adoption of cover crops and multispecies leys, mixed crop-livestock systems and resource sharing. These practices, categorised as manure/fertiliser-, feed- or system-based management, were generally perceived by farmers as 'common-sense', being both practical and acceptable for implementation (Evans et al., 2025).

This study addresses a critical research gap by being the first to integrate N efficiency into a farm-level MACC framework, thereby linking GHG mitigation with nutrient management. We hypothesise that this novel approach could identify circular practices that simultaneously reduce emissions and improve nutrient cycling, while also helping to reveal and avoid potential trade-offs. We test this hypothesis by modelling the adoption of eight circular farming practices across five UK farm types (mixed, arable with livestock, dairy, dairy-beef and beef-sheep). This study does not consider carbon sequestration, despite its importance for climate change mitigation as a major sink for atmospheric CO_2 (Kamyab et al., 2024) and its critical role in achieving net zero agriculture (McNicol et al., 2024). We excluded it to avoid overestimating the contribution of circular practices, given its strong context-specificity and the likelihood that many UK grassland systems are already close to soil carbon saturation (Jordon et al., 2024). This study focuses on waste reduction, resource recycling and lower external inputs as strategies to reduce GHG emissions, with only limited direct impacts on carbon sequestration. Using mass flow models and average UK Farm Business Survey (FBS) data (Defra, 2023a), this study quantifies changes in inputs, outputs and losses, highlighting the practical opportunities and cost-effectiveness of circular practices for reducing farm-level N loss and GHG emissions.

2. Materials and methods

This section describes the methods, including the regional data used to construct model farm types, the approach for estimating baseline GHG emissions and N balances, the models applied to simulate changes, and the procedure for constructing the MACC.

2.1. Description of livestock farming systems

The five farm types were designed to be representative of the main farming systems in England and Wales (Table 1). These were selected using the UK FBS (Defra, 2023a), a stratified annual panel survey providing detailed physical, environmental and financial data on English and Welsh farms. Selection focused on regions where livestock-arable interactions could be modelled. The FBS is representative of UK agriculture, covering diverse farm types, structures and geographic regions (see Defra 2023a for details).

This study was conducted at the farm-level, which is the most relevant spatial scale for assessing the impact of adopting circular practices aimed at reducing farm-level GHG emissions, enhancing nutrient cycling and improving farm profitability. Due to limited data availability and to

Table 1
Characteristics of the five farm types, based on average values from UK FBS Region Reports 2018-2020, with standard errors provided where available to illustrate inter-annual variability (Defra, 2023a).

Variables	Farm types				
	Mixed	Arable	Dairy	Dairy-Beef	Beef-Sheep
Location (England and Wales)	West Midlands	West Midlands	Northwest	Northwest	Wales
NUTS2/3 region[a]	UKG2	UKG2	UKD6	UKD4	UKL12
Farms in sample	26 (±0.88)	32 (±2.40)	50 (±1.15)	50 (±1.15)	85 (±1.20)
Utilised agricultural area (ha)	151.1 (±9.08)	156.7 (±5.96)	125.3 (±2.02)	125.3 (±2.02)	103.1 (±2.93)
Arable cropland (ha)					
Winter wheat	31.3 (±5.14)	62.7 (±10.94)	0	0	0
Winter barley	7.1 (±1.24)	11.9 (±2.02)	1.8 (±0.13)	1.8 (±0.13)	3.2 (±0.19)
Spring barley	13.1 (±0.36)	11.7 (±2.80)	2.1 (±0.41)	2.1 (±0.41)	0
Winter oilseed rape	7.8 (±1.04)	23.8 (±0.35)	0.2 (±0.11)	0.2 (±0.11)	0
Winter field beans	2.8 (±0.18)	9.9 (±1.57)	0	0	0
Grassland and forage (ha)					
Lowland grazing grass	59.6 (±3.18)	15.8 (±0.61)	82 (±1.77)	82 (±1.77)	69 (±1.49)
Rough grazing	0	0	5.4 (±0.13)	5.4 (±0.13)	6.3 (±0.75)
Silage grass	0	0	0	0	22 (±1.45)
Temporary grassland	16.8 (±2.07)	3.3 (±0.24)	33.8 (±0.46)	33.8 (±0.46)	0
Forage maize	12.6 (±0.11)	17.6 (±1.88)	0	0	0
Inorganic ammonium-nitrate fertiliser (kg N ha^{-1} yr^{-1})	105 (±9.73)	146 (±18.20)	126 (±10.56)	126 (±10.56)	41 (±2.17)
Atmospheric N deposition (kg N ha^{-1} yr^{-1})[b]	8.9	8.9	8.9	8.9	8.9
Biological N fixation (kg N ha^{-1} yr^{-1})[c]	20.5	20.5	20.5	20.5	20.5
Livestock (numbers)					
Dairy cow	0	0	199 (±3.30)	159 (±3.30)	0
Dairy calf	0	0	58 (±4.49)	105 (±4.49)	59 (±3.44)
Dairy heifer	0	0	46 (±0.03)	45 (±0.03)	0
Beef cow	0	0	0	0	30 (±2.62)
Beef cattle	114 (±13.90)	23 (±3.46)	5 (±0.27)	60 (±0.27)	29 (±3.44)
Ewe	200 (±20.55)	40 (±8.19)	43 (±1.51)	43 (±1.51)	414 (±9.11)
Lamb	242 (±32.40)	41 (±6.43)	73 (±7.25)	73 (±7.25)	284 (±6.09)
Pig gilt	124 (±30.20)	0	0	0	0
Hen laying	408 (±331.70)	0	0	0	0
Hen broiler	714 (±362.54)	0	0	0	0
Concentrate fed (t $farm^{-1}$ yr^{-1})[d]	183.8 (±14.78)	10.4 (±0.32)	795.8 (±16.64)	612.7 (±12.81)	40.2 (±1.58)
Purchased bedding (t $farm^{-1}$ yr^{-1})[d]	152.8 (±3.53)	17.5 (±4.39)	411.0 (±13.51)	390.8 (±12.83)	62.6 (±0.45)

[a] NUTS regions are part of the "Nomenclature of Territorial Units for Statistics" (NUTS) system established by the European Union (EU) to create standardised geographical regions for statistical and economic analysis across EU member states (Eurostat, 2024).
[b] Data sourced from official critical load maps (Defra, 2023b).
[c] Baseline assumption for non-legume-managed grassland derived from a global dataset of terrestrial biological nitrogen fixation (Reis Ely et al., 2025), used here to represent conservative estimates and to subsequently evaluate their greatest potential.
[d] Mass obtained by dividing farm costs (Defra, 2023a) by market prices (AHDB, 2023a, 2023b).

prevent farms from being identifiable, average data for specific farm types within NUTS2 regions (NUTS3 for the Welsh farm type) were used (Eurostat, 2024). The analysis used average values for the 3-year period 2018–2020 (Table 1), capturing recent, reliable historical data that sufficiently represents current practices and policies. This approach also minimised the impact of annual variability—such as fluctuations in weather, pest pressures and market conditions—while providing a more stable baseline for analysis.

Although these farm types are referred to as 'livestock systems', with circular practices primarily targeting manure and feed (nutrient) management within livestock production, all farm types produced both crop and animal products. Ruminants are the dominant livestock and are better adapted to more circular systems focused on integrating crop and livestock production at the farm-level due to their ability to deposit excreta while grazing grass and forage resources. Specialist pig and poultry systems, which typically have less land area available to grow feed crops and spread manure, but can contribute to more circular systems at the regional-level by recycling food processing by-products as feed (van Zanten et al., 2019), were excluded from this study, as it is focused on the farm-level.

For all applicable farm types, dairy and beef cattle were assumed to graze for 7 months of the year and be housed for 5 months, while sheep grazed year-round (Nix, 2024). On the mixed farm, pigs and poultry were assumed to be housed for 6 months (Nix, 2024). The mass of purchased concentrate feed and bedding are shown in Table 1. Details about diet formulation and bedding material can be found in Section 1 of the Supplementary Material.

To assess the maximum potential impact of circular practices aimed at improving liquid slurry management (e.g. solid-liquid slurry separation and anaerobic digestion), it was assumed that manure from the mixed (pig enterprise only), dairy and dairy-beef farms was managed entirely as liquid slurry. This slurry was presumed to be stored in an uncovered earth-bank lagoon – a practice used by 31% of livestock holdings with slurry storage facilities (Defra, 2024a) – and applied to grassland and arable land using a broadcast spreader (splash plate), reflecting the most common current practice. This approach enabled an evaluation of a substantial potential improvement from adopting circular practices.

To evaluate the potential impact of circular practices targeting solid manure management (e.g. composting), it was assumed that all manure on the mixed farm (poultry, beef and sheep enterprises), arable, and beef-sheep farms was managed as solid manure. This solid manure was stored uncovered at field sites – as practiced by 66% of livestock holdings with solid manure storage facilities (Defra, 2024a) – and surface-applied to grassland and arable land using a tractor with a rear-discharge spreader. This scenario also reflects common current practices and facilitates an evaluation of the potential benefits of circular practices.

All straw bedding was managed as solid manure across all farm types and handled according to the described practices. No manure was assumed to be imported or exported, as baseline farms remained below the Nitrate Vulnerable Zone (NVZ) limits (Defra, 2024b). All farms purchased and applied synthetic fertiliser (ammonium-nitrate – UK produced; AN UK) at rates of 41–146 kg N ha^{-1} yr^{-1} (Defra, 2023a) with a unit cost of £390 t^{-1} AN UK (Nix, 2024).

2.2. Baseline GHG emissions

Farm activity and land use data from the FBS were used to estimate baseline GHG emissions for each farm type using Agrecalc (2024), a farm carbon calculator developed by Scotland's Rural College (Agrecalc Ltd., Edinburgh). Agrecalc conforms to ISO 14044 Life Cycle Assessment (LCA) guidelines and complies with PAS 2050:2011 carbon footprinting standards. The tool adopts a 'cradle-to-gate' system boundary, with emissions allocated on an economic basis. For livestock enteric methane (CH_4) and nitrous oxide (N_2O) emissions from excreta deposited on grazing land, Agrecalc employs IPCC (2019) Tier 2 country-specific emission calculations. Similarly, all CH_4 and N_2O emissions from manure management use IPCC (2019) Tier 2 emission factors (EFs), which account for dietary and climatic characteristics. Direct soil N_2O emissions following fertiliser and manure application also utilise IPCC (2019) Tier 2 EFs (i.e. direct N_2O EF are 0.75, 0.33 and 1.01% of applied N for slurry, farmyard manure and poultry manure, respectively; BEIS, 2023).

IPCC (2019) Tier 1 calculations are employed for N_2O emissions from crop residues and indirect N_2O emissions related to volatilisation and leaching. For inputs, energy use values were sourced from figures published in the Greenhouse Gas Protocol (Defra, 2012). Embedded fertiliser emissions (i.e. associated with fertiliser production) were obtained from Fertilisers Europe (2018). For purchased concentrate feed, Agrecalc used the Dutch Feedprint database (Vellinga et al., 2013).

Emissions were expressed as carbon dioxide equivalents (CO_2e) using Global Warming Potential over 100 years (GWP_{100}) from the sixth assessment report (AR6; IPCC, 2021), with GWP values of 27 for CH_4 and 273 for N_2O (IPCC, 2021). Emissions were expressed as annual whole-farm emissions (Mg CO_2e yr^{-1}), emissions per unit of crude protein (CP) output (kg CO_2e kg^{-1} CP output yr^{-1}), and emissions per hectare (kg CO_2e ha^{-1} yr^{-1}).

2.3. Circular practices scenario modelling – MACCs

Scenarios of enhanced farm-level circular practices were created (Table 2) to assess their impact on GHG reduction, cost-effectiveness and N efficiency across farm types. The methodological approach used to model these impacts is summarised in Fig. 1, with an illustrative example of a circular practice scenario provided in Fig. 2. Circular practices were selected from a comprehensive list compiled by circularity experts in the CircAgric-GHG project (https://www.circagric.org/), prioritising those that maximise circularity under the '3Rs' framework—Reduce, Reuse/Recycle, and Regenerate (Velasco-Muñoz et al., 2021). Selection focused on technologically feasible yet underutilised practices in UK farming, as identified in recent Farm Practice Surveys (Defra, 2019; 2022) and aligned with stakeholder priorities from interviews and focus groups (Evans et al., 2025). Between six and seven circular practices were individually assessed for each farm type, depending on their applicability.

The different circularity scenarios were not modelled directly within Agrecalc. Instead, Agrecalc was only used to generate a baseline GHG footprint for each farm type. Scenario impacts were then estimated as adjustments to this baseline. Changes in resource use (e.g. feed, fertiliser, manure) were quantified using mass flow models in Excel to reflect differences in inputs and outputs under each circular practice.

Table 2
Circular practices scenarios created to assess the impact on GHG emissions, cost-effectiveness and N efficiency across farm types.

Circular practices	Descriptions	Farm types*	Inclusion in previous UK MACCs
Manure/fertiliser-based			
Slurry separation	Mechanical screw press separation of all livestock slurry, produced on-farm, to increase N crop-availability in the liquid fraction and to reuse the solid fraction as a bedding material, thereby reducing the inputs of synthetic fertiliser and purchased bedding	M,D, DB	None
Composting of manure	Composting of all solid manure, produced on-farm, in turned windrows to reduce the volume of manure to spread	M,A, BS	Moran et al. (2011)
Anaerobic digestion	On-farm, small-scale (<250 kW) anaerobic digestion of all slurry and farmyard manure, produced on-farm, to increase N crop-availability in digestate (rapidly incorporated to minimise NH_3 emissions) and reduce synthetic fertiliser input, while producing biogas, a source of renewable energy	M,A,D, DB,BS	Eory et al. (2015), Moran et al. (2011), Barnes et al. (2022)
Biosolids application	Apply recycled biosolids from a regional wastewater treatment plant on 20% of each farm area to reduce synthetic fertiliser input	M,A,D, DB,BS	None
Feed-based			
Alternative feed	Use alternative feed ingredients – brewers' grains (a by-product of the brewing sector) and home-grown barley – to reduce concentrates input and reuse crop residue (straw) as bedding material	M,A,D, DB,BS	None
Cover crops	Grow a diverse grazable cover crop mix (SAM2; Cotswold Seeds, 2024) containing legumes between arable crop rotations and as a multispecies ley on temporary grassland to increase biological N fixation and home-grown forage, to reduce synthetic fertiliser and concentrate inputs	M,A,D, DB,BS	Eory et al. (2015), Moran et al. (2011), Barnes et al. (2022)
System-based			
Mixed crop-livestock system	Arable and dairy farms proportionally exchange a portion of their production systems: Arable farm incorporates additional livestock production while the dairy farm increases crop production. This exchange results in increased manure availability on the arable farm, reducing synthetic fertiliser input, and increased crop residue availability on the dairy farm, reducing purchased bedding inputs. Significant change in farm activities and land use. Both farms transition to mixed	A,D	None

(*continued on next page*)

Table 2 (*continued*)

Circular practices	Descriptions	Farm types*	Inclusion in previous UK MACCs
	crop-livestock systems, integrating crop and animal production within each farm		
Sharing resources	Sharing resources – machinery sharing and 'straw-for-muck' deal (arable and dairy farms only) – to increase production efficiency and reduce synthetic fertiliser and purchased bedding inputs. No change in farm activities and land use	M,A,D, DB,BS	None

* M = mixed; A = arable; D = dairy; DB = dairy-beef; BS = beef-sheep farm types.

Associated changes in GHG emissions were derived by applying mitigation or abatement rates taken from peer-reviewed literature and technical reports. For example, changes in N_2O and CH_4 emissions from manure management practices were accounted for using empirical evidence (e.g. Chadwick et al., 2011). As fertiliser and manure application to land represent the dominant source of on-farm N_2O emissions, changes in direct and indirect N_2O emissions arising from altered application rates were explicitly calculated across all scenarios. This approach ensured that each scenario reflected both the biophysical changes in resource flows and the best available evidence on emissions responses. Agrecalc does not yet include a built-in module for most circular practices. A more detailed technical description of the scenarios and modelling approach is available in the Supplementary Material (see 2 and Tables S1-9).

Circular practices can be ranked by their impact on farm-gate N balances, calculated by subtracting total N outputs (crop and animal products and sales) from total N inputs (fertilisers, concentrate feed, bedding, biological fixation, atmospheric deposition and purchased animals). Input and output data were sourced from FBS Region Reports and regional average assumptions (Table 1). The calculations for baseline N inputs and outputs across farm types are detailed in Section 3 of the Supplementary Material. Baseline farm-gate N balances were positive for all farm types.

The impact of circular practices on these balances was expressed as changes relative to baseline, quantified as N balance change (kg N) per Mg CO_2e mitigated. Positive values indicated increased N surplus, suggesting potential inefficiencies or losses (leaching, volatilisation, emissions), while negative values reflected improved N use efficiency. Changes in fertiliser, concentrate feed and bedding inputs were not assumed arbitrarily. Instead, they were quantified using Excel-based mass-flow models that estimated how each circular practice affected (i) the nutrient content and crop-availability of manures or digestate (based on literature-derived coefficients), (ii) the quantities of materials available for application or on-farm use, and (iii) the resulting requirement for externally purchased inputs. These calculations follow established nutrient-budgeting methodologies applied in UK agriculture (AHDB, 2024). Because these changes occur prior to within-field soil processes, a farm-gate accounting approach is appropriate for estimating associated adjustments in input demand, embedded emissions and costs.

The circular practices can also be ranked in terms of their cost-effectiveness, specified as £ per Mg CO_2e mitigated. Positive values indicated costs to the farmer, while negative values signified savings. System-based circular practices (e.g. mixed crop-livestock system, resource sharing) primarily affected outputs, while the manure/fertiliser- and feed-based circular practices influenced inputs. Costs were derived from standard farm management data (Nix, 2024) and industry sources, with capital costs annualised. Changes in inputs, outputs, transport, labour and machinery were included as relevant.

In this study, a 'bottom-up' MACC (Eory et al., 2015, 2020) approach ranked circular practices by increasing cost and N balance per unit CO_2e abated (vertical axis). Annual emission savings (horizontal axis) were calculated as the difference between baseline and post-adoption emissions, with associated costs and N balances similarly assessed relative to baseline.

3. Results

This section presents the results, beginning with baseline N balances and GHG emission profiles for each farm type, including emission intensities, and then outlining the cost-effectiveness and N efficiency MACCs for each system.

3.1. Baseline scenarios

Farm-level N balances and GHG emissions varied widely across farm types due to differences in land use, management intensity and farm size (Table 3). N balances ranged from 5,870 kg N yr^{-1} on the arable farm to 32,656 kg N yr^{-1} on the dairy farm. Total emissions were lowest for the arable farm (887 Mg CO_2e yr^{-1}) and highest for the dairy-beef farm (3,327Mg CO_2e yr^{-1}).

Emission intensity per kg crude protein (CP) output was lowest on the arable farm (7.2 kg CO_2e kg^{-1} CP output yr^{-1}) and highest on the extensive beef-sheep farm (96.1 kg CO_2e kg^{-1} CP output yr^{-1}). Per hectare emissions were also lowest for the arable farm (5,664 kg CO_2e ha^{-1} yr^{-1}) and highest for the dairy-beef farm (26,549 kg CO_2e ha^{-1} yr^{-1}), reflecting the contribution from enteric methane (CH_4) emissions.

Emission profiles varied across farm types (Fig. 3). Enteric methane was the dominant source for the mixed, dairy, dairy-beef and beef-sheep farms (46–64% of total emissions) but lower for the arable farm (20%) (reflecting their small number of grazing sheep). Nitrous oxide (N_2O) from fertiliser application was a key contributor for the arable farm (34%) but lower across the other farm types (6–11%). Across all farms, embedded CO_2 emissions from external inputs (e.g. fertiliser, concentrate feed, bedding) accounted for 13–35% of total emissions, highlighting these inputs as major emissions hotspots that could be effectively targeted through the adoption of circular practices.

3.2. Farm-level MACCs for circular practices scenarios

The impact of the circular practices on total farm-level GHG emissions is summarised in Table 4. To further evaluate their abatement potential, cost-effectiveness and N efficiency across different farm types, MACCs were constructed. Fig. 4 presents these MACCs, highlighting the circular practices most effective for GHG mitigation, cost savings and improving N efficiency within specific farming systems.

Recycled biosolids application was excluded from the N efficiency MACC (Fig. 4.ii) due to their minimal GHG mitigation potential (as shown in Fig. 4.i) and a net increase in N input. Although this N source is recycled, it significantly inflates the N input per unit of GHG abated compared to other practices. Including biosolids application would have skewed the *y*-axis scale, obscuring changes for other circular practices.

System-based circular practices (mixed crop-livestock system and resource sharing) were analysed separately to the MACCs due to their collaborative nature. Sharing resources, excluding the 'straw-for-muck' deal (between the arable and dairy farms only), did not affect total farm emissions but improved production efficiencies, reducing product emissions by 6.9–45.2% (Table 5). The mixed crop-livestock system had mixed effects, decreasing product emissions by 19.6% on the dairy farm but increasing them by 25.3% on the arable farm due to higher CP output per hectare of crop production compared to livestock.

Manure/fertiliser-based approaches reduced total farm emissions but had no effect on product emissions. Feed-based circular practices, such as using home-grown barley as an alternative feed ingredient, increased product emissions (Table 5) due to reduced crop product output. Cover crops improved cash crop yields, lowering product

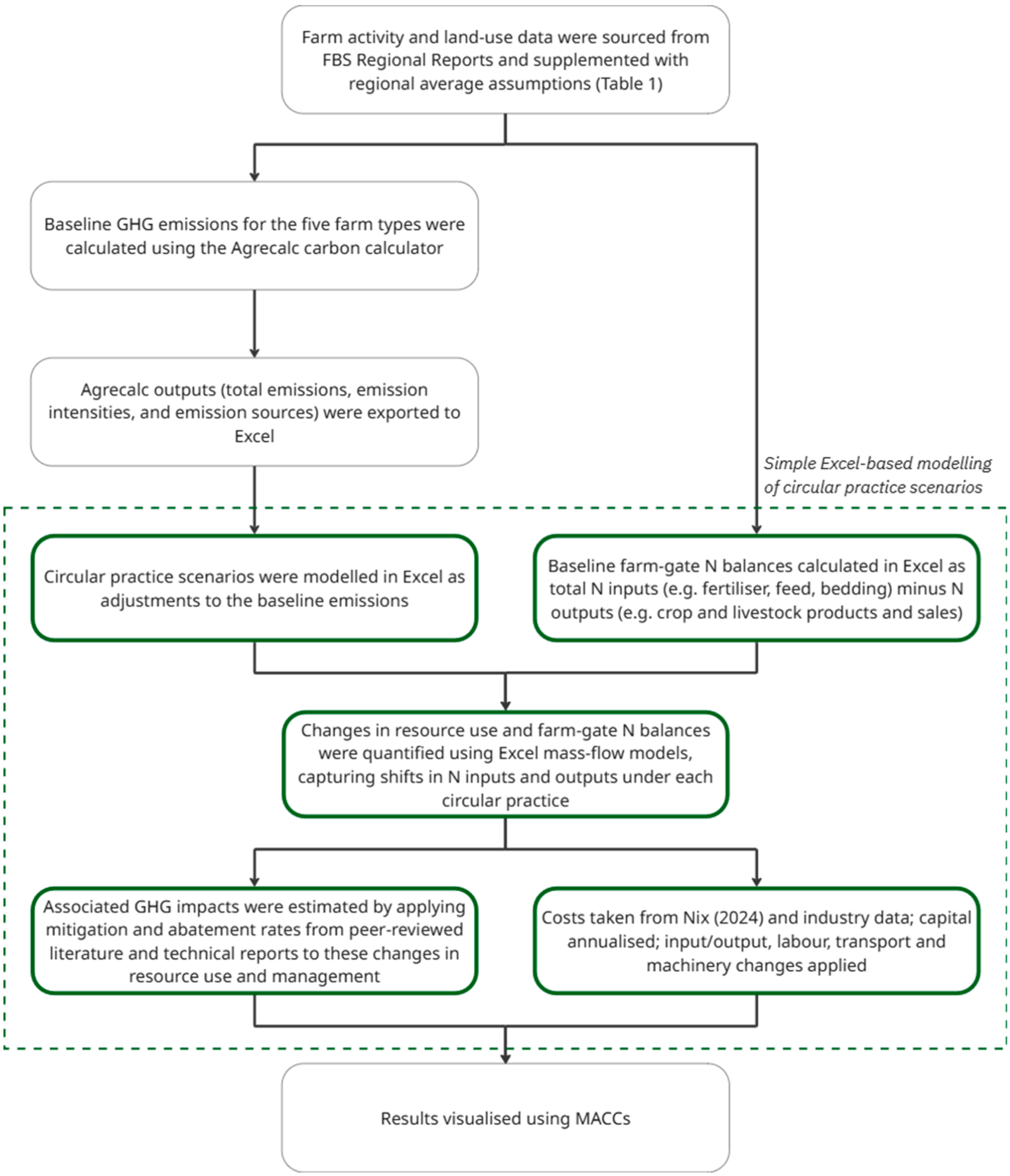

Fig. 1. Methodological flow chart for modelling the impacts of circular practice scenarios.

emissions by 2.9–33.2% across all farms.

3.2.1. *Mixed farm*

Anaerobic digestion (AD) achieved the largest emission reduction (5.5%) and improved N efficiency by reducing the N balance by 13 kg N Mg CO_2e^{-1} yr^{-1} but was not cost-effective. Using alternative feed ingredients was the most cost-effective practice, reducing emissions by 4.7% and saving £200 Mg CO_2e^{-1} yr^{-1} by lowering concentrate feed use. Cover crops were the most N-efficient option, reducing the N balance by 18 kg N Mg CO_2e^{-1} yr^{-1} through lower N fertiliser and concentrate feed inputs, enhanced biological N fixation and increased cash crop yields.

3.2.2. *Arable farm*

Cover crops achieved the largest emission reduction (28.0%), saved £27 Mg CO_2e^{-1} yr^{-1} and reduced the N balance by 28 kg N Mg CO_2e^{-1} yr^{-1} due to lowered synthetic fertiliser use and increased cash crop yields. Using alternative feed ingredients was the most cost-effective practice (saving £122 Mg CO_2e^{-1} yr^{-1}) but had minimal impact on emissions (0.6% reduction) and no effect on N balances, as the same mass of N was still imported in the form of brewers' grains and home-grown feed diverted from saleable crop products.

3.2.3. *Dairy farm*

AD achieved the largest emission reduction (7.8%) and reduced the N balance by 15 kg N Mg CO_2e^{-1} yr^{-1}, but at a cost of £94 Mg CO_2e^{-1} yr^{-1}. Solid-liquid slurry separation was the most cost-effective and N-efficient option, reducing emissions by 4.8%, saving £129 Mg CO_2e^{-1} yr^{-1}, and reducing the N balance by 17 kg N Mg CO_2e^{-1} yr^{-1} due to

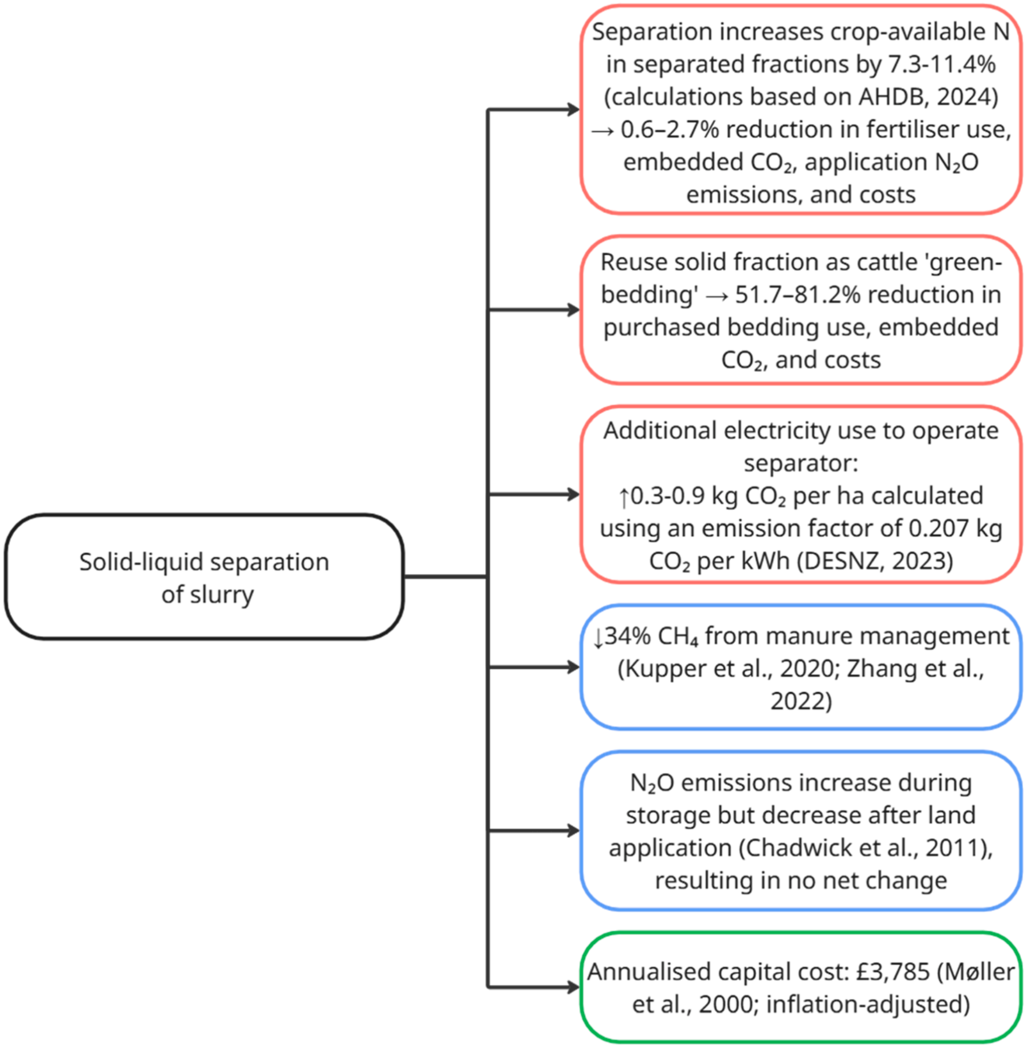

Fig. 2. Example flow diagram for the solid–liquid slurry separation circular scenario, showing key changes in inputs (red), GHG emissions (blue) and costs (green).

Table 3
Baseline farm-level N balances, total GHG emissions, product emissions and emissions per unit area for the different farm types.

Farm types	Baseline farm-level N balances (kg N yr^{-1})	Baseline farm-level emissions (Mg CO_2e yr^{-1})	Baseline product emissions (kg CO_2e kg^{-1} CP output yr^{-1})	Baseline emissions per unit area (kg CO_2e ha^{-1} yr^{-1})
Mixed	15,241	1,959	26.7	12,965
Arable	5,870	887	7.2	5,664
Dairy	32,656	2,965	39.0	23,665
Dairy-beef	30,469	3,327	57.0	26,549
Beef-sheep	7,077	1,028	96.1	9,967

lowered fertiliser and bedding inputs.

3.2.4. Dairy-beef farm

Like the specialised dairy farm, AD achieved the largest emission reduction (7.8%) and reduced the N balance by 11 kg N Mg CO_2e^{-1} yr^{-1} but at a lower cost of £80 Mg CO_2e^{-1} yr^{-1}. Solid-liquid slurry separation was the most cost-effective practice, reducing emissions by 4.4%, saving £103 Mg CO_2e^{-1} yr^{-1}, and reducing the N balance by 14 kg N Mg CO_2e^{-1} yr^{-1}. Cover crops ranked highest for N efficiency, reducing the N balance by 16 kg N Mg CO_2e^{-1} yr^{-1}.

3.2.5. Beef-sheep farm

Multispecies leys (cover crops) achieved the largest emission reduction (4.4%), reduced the N balance by 21 kg N Mg CO_2e^{-1} yr^{-1}, and were the most cost-effective (saving £163 Mg CO_2e^{-1} yr^{-1}), mainly by eliminating the need to purchase concentrate feed. AD was the most N-efficient practice, reducing the N balance by 23 kg N Mg CO_2e^{-1} yr^{-1} due to lower N fertiliser inputs.

3.3. Collaborative circular practices

The mixed crop-livestock system increased total farm-level GHG emissions by 11.4% on the arable farm but reduced them by 5.0% on the dairy farm, primarily due to changes in ruminant livestock numbers and their associated enteric CH_4 emissions. However, overall, this practice resulted in a net 1.2% reduction in combined total emissions across both farms (Fig. 5). Sharing resources through a ‘straw-for-muck’ exchange lowered emissions by 4.5% on the arable farm and 0.8% on the dairy

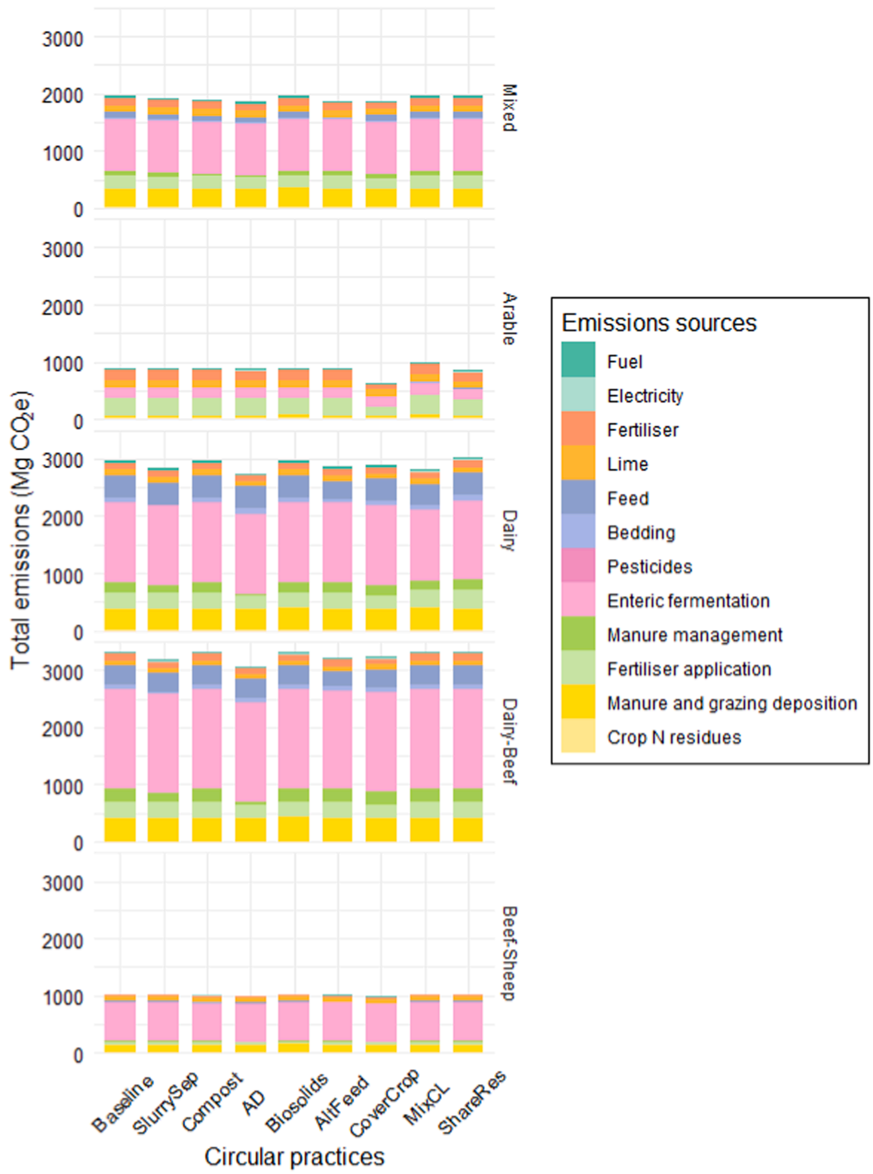

Fig. 3. Comparison of total farm-level emissions (Mg CO_2e) in the baseline farm types and the subsequent impact of circular practices implemented individually. Circular practices include solid-liquid slurry separation *(SlurrySep)*, composting farmyard manure *(Compost)*, anaerobic digestion *(AD)* of slurry and farmyard manure, application of recycled biosolids *(Biosolids)*, use of alternative feed ingredients *(AltFeed)*, adoption of cover crops and multispecies leys *(CoverCrop)*, mixed crop-livestock systems *(MixCL)*, and resource sharing *(ShareRes)*.

Table 4
Percentage changes in total farm-level GHG emissions from adoption of individual circular practices across the five farm types (- = not applicable).

Circular practices	Total farm-level emission change (%)				
	Mixed	Arable	Dairy	Dairy-Beef	Beef-Sheep
Manure/fertiliser-based					
Slurry separation	-2.3	-	-4.8	-4.4	-
Composting	-3.1	-0.2	-	-	-0.8
Anaerobic digestion	-5.5	-1.0	-7.8	-7.8	-3.0
Biosolids application	-0.1	-0.2	-0.2	-0.1	-0.2
Feed-based					
Alternative feed	-4.7	-0.6	-3.5	-3.2	-1.2
Cover crops	-4.5	-28.0	-3.0	-2.7	-4.4

Note: System-based circular practices were excluded as they were assessed at the inter-farm level rather than the individual farm level.

farm, yielding a net reduction of 1.6% across both farms (Fig. 5), primarily through reduced purchased synthetic fertiliser and bedding inputs.

4. Discussion

This study assessed the GHG mitigation potential, cost-effectiveness and N efficiency of circular farming practices across various UK farm types. The results highlight that while circular practices may offer only modest emission reductions, they can provide significant cost savings and improve nutrient management. This section explores key opportunities, trade-offs, and policy implications for their adoption.

4.1. Emission baselines and the strategic role of circular practices

Establishing an accurate baseline for GHG emissions is crucial for evaluating the impact of circular practices. This study observed notable variation in baseline emissions between farm types, reflecting differences in land use, management intensity and farm size. These baselines were consistent with values reported in the literature for beef-sheep

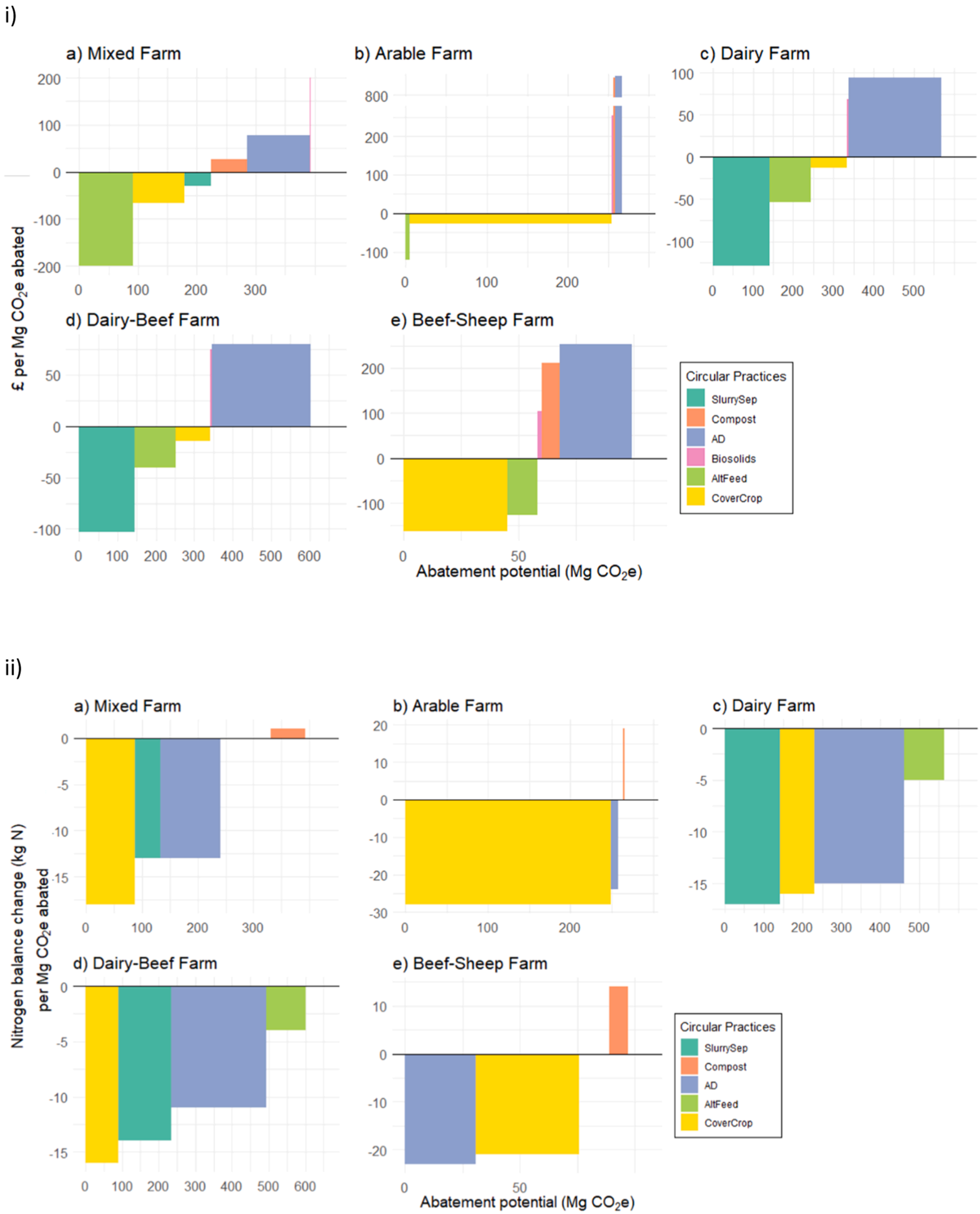

Fig. 4. Marginal Abatement Cost Curves (MACCs) based on i) cost-effectiveness and ii) nitrogen efficiency for circular practices and farm types. Note the variation in scale of the axes.

Table 5
Comparison of product GHG emissions in the baseline farm types and the subsequent impact of adopting individual circular practices.

Circular practices	Product emission change (%)				
	Mixed	Arable	Dairy	Dairy-beef	Beef-Sheep
Feed-based					
Alternative feed	13.8	0.2	0.4	2.0	29.7
Cover crops	-10.0	-33.2	-3.1	-2.9	-6.0
System-based					
Mixed crop-livestock system	-	25.3	-19.6	-	-
Sharing resources	-8.0	-21.2	-45.2	-7.5	-6.9

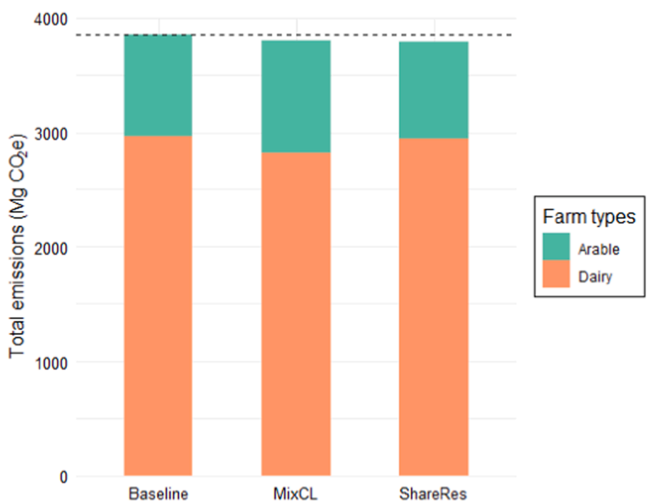

Fig. 5. Comparison of the combined total emissions (Mg CO_2e) across the baseline arable and dairy farms and subsequent impact of adopting the system-based, collaborative circular practices – mixed crop-livestock system *(MixCL)* and sharing resources through a 'straw-for-muck' deal *(ShareRes)*.

(McNicol et al., 2024) and dairy farms (Sorley et al., 2024), as well as with regional benchmarking data (Agrecalc, 2024). The arable farm, with the fewest livestock, exhibited both the lowest product and total emissions; highlighting the potential for greater emissions reduction gains in livestock systems (Audsley and Wilkinson, 2014). Baseline N balances were consistent with those reported for Irish farming systems by Buckley et al. (2015), though field-level estimates, as recommended by van Leeuwen et al. (2019), would provide greater precision to support management decisions.

While this study did not consider carbon sequestration, extensive grassland-based ruminant livestock systems may sequester and store more carbon, partially or fully mitigating other GHGs within the system (Jordon et al., 2024). Net GHG emissions from these systems are therefore likely to be lower than our results suggest. To overcome uncertainties and improve accuracy in estimating soil carbon sequestration capacity and rate (Jordon et al., 2024), future research could integrate process-based models, such as the DeNitrification-DeComposition (DNDC; Khalil et al., 2020) or DayCent (Dhaliwal et al., 2026) model.

Enteric methane contributed the largest share of total emissions (46–64%) across the livestock farming systems, aligning with previous findings by Hyland et al. (2016b) and McNicol et al. (2024). This proportion is slightly higher than the GHG emission profiles reported for EU livestock systems (36%; Lesschen et al., 2011) and those in China, where CH_4 from enteric fermentation accounts for 23% of emissions from meat production and 30% from milk production (Yue et al., 2017). Targeted mitigation measures, such as using 3-Nitrooxypropanol (3NOP) as a feed additive and improving livestock productivity, were recently shown to reduce farm-level emissions by 11.9% and 8.7%, respectively (McNicol et al., 2024) and are integrated into the UK Government's Carbon Budget Delivery Plan (Cabinet Office, 2023). The plan also highlights the role of cover crops and multispecies leys.

The inclusion of other circular practices in the Carbon Budget Delivery Plan is limited. Although embedded CO_2 emissions in external inputs and energy contributed less to total emissions (13–35% in this study; 19% for beef-sheep production in McNicol et al. (2024); 31% for crop production in Głąb and Sowiński (2019)), these inputs represent significant emission hotspots that have received less attention. Circular practices in this study targeted minimising these inputs while also considering wider benefits for nutrient management and farm profitability. Despite their modest mitigation potential compared to enteric CH_4 reduction strategies, circular practices offer broader benefits that may enhance their appeal to farmers, making them a valuable component of wider mitigation efforts. Effective policies should support both approaches, potentially using circular practices as a stepping stone to encourage farmers to engage with broader mitigation strategies.

Simply promoting emissions reduction often fails to motivate farmers (Jebari et al., 2024). Instead, framing mitigation measures within a broader circularity approach—emphasising cost savings and improved nutrient management—could enhance adoption by aligning with diverse farming priorities (Hyland et al., 2016a), as demonstrated by Evans et al. (2025).

The differing rankings of GHG abatement potential based on cost-effectiveness and N efficiency underscore the need for policies that balance economic and environmental goals to avoid trade-offs. Recognising that circular practice rankings depend on the chosen priority—cost-effectiveness or N efficiency—could support more targeted, context-specific policy interventions, enhancing adoption and impact. Since the cost-effectiveness of mitigation measures varies across farming sectors, leading to uneven implementation, allowing farmers flexibility to adopt measures suited to their specific contexts could improve uptake and effectiveness (Fellmann et al., 2021). Farmers are more likely to adopt practices that align with their priorities and deliver multiple benefits (Evans et al., 2025).

4.2. *Circular practice performance: balancing mitigation, efficiency and cost*

All the manure/fertiliser- and feed-based circular practices assessed effectively reduced farm-level GHG emissions, with most also improving N efficiency, but only about half were cost-effective. The analysis revealed significant variation in the GHG mitigation potential, N efficiency and cost-effectiveness of circular practices across farm types, highlighting the need to incentivise a diverse range of mitigation options.

The mixed farm showed significant potential for GHG emissions reduction (4.7%) by substituting conventional concentrate feed for alternative feed ingredients. This aligns with other studies showing that alternative feed ingredients can significantly reduce GHG emissions by avoiding land use change associated with soya production (Leinonen et al., 2018). The higher fat content of some alternative feeds can reduce enteric CH_4 emissions, as demonstrated by Duthie et al. (2015) and Moate et al. (2011) for brewers' grains. However, nutritional, technological and distributional constraints exist (Yang et al., 2021), and regulations may limit the use of certain alternative feeds, such as food waste (Salemdeeb et al., 2017). Amid increases and volatility in the price of concentrate feed (AHDB, 2023a), many farmers will likely seek alternative feed ingredients, both home-grown and from the wider food-waste system, to increase their economic resilience (Evans et al., 2025).

Solid-liquid slurry separation was the most cost-effective circular practice for the dairy and dairy-beef farms. Emission reductions were primarily due to higher N crop-availability in the separated fractions (AHDB, 2024), lowering synthetic N fertiliser use and replacing purchased straw bedding with recycled 'green-bedding' (Leach et al., 2015).

Separating slurry can also reduce storage needs by ~7% (Møller et al., 2000), aiding compliance with NVZ requirements (Defra, 2024b) and enabling low-emission slurry spreading (LESS) methods (Lyons et al., 2021). LESS could further enhance GHG mitigation and reduce phosphorus (P) loss, supporting water quality and preserving P resources (Schoumans et al., 2015). To capture these broader benefits, MACCs could be complemented by Life Cycle Assessment (LCA).

Cover crops had the greatest mitigation potential on the arable farm (28% GHG reduction in total emissions), while sowing the same mix as a multispecies ley achieved the highest reduction on the beef-sheep farm (4.4% reduction in total emissions). These reductions were comparable to those reported by Abdalla et al. (2019) (2.06 Mg CO_2e ha^{-1} yr^{-1}) for the same measure, and are primarily due to increased biological N fixation and grazable forage, lowering synthetic N fertiliser use (by 50% on the arable farm) and concentrate feed inputs, respectively. When integrated into crop-livestock systems and managed with a circular approach, including grazing termination (Jebari et al., 2023), cover cropping proved cost-effective (saving £13–163 Mg CO_2e^{-1} yr^{-1}), a key factor influencing adoption (Jebari et al., 2024). Its economic viability is expected to improve with rising fertiliser and feed costs (The Andersons Centre, 2022). Cover crops also provide multiple ecosystem services (Blanco-Canqui et al., 2015) and are promoted through agri-environment schemes, such as the Sustainable Farming Incentive in England (Defra, 2023c) and Sustainable Farming Scheme in Wales (Welsh Government, 2024). These broader benefits require better quantification (Schipanski et al., 2014) and should be considered alongside MACCs to support informed policy and farm-level decision-making.

4.3. Scaling circular practices: from farm to region

While most circular practices were assessed at the farm level, mixed crop-livestock systems and resource sharing were considered at inter-farm scales. The mixed crop-livestock system scenario, which redistributed arable and livestock production between the arable and dairy farms to increase interactions between cropping and livestock activities and optimise resource use, showed greater benefits at a regional level. GHG mitigation was more pronounced regionally than at the farm level, aligning with the findings of Marton et al. (2016) and Mosnier et al. (2022). Uniform emission reduction targets for all farm types may be ineffective; instead, focusing on efficiency improvements in high-emission systems, such as intensive livestock farms, could achieve greater overall reductions, even if emissions rise slightly in less intensive systems. This supports the case for regional rather than farm-level targets, which account for heterogeneous abatement costs but also require consideration of transaction costs, political acceptability, and a mix of policy instruments such as carbon taxes and compensation schemes (Tarruella et al., 2025).

Mixed farming systems may offer greater potential to reduce emissions than specialised systems, but their implementation is often constrained by real-world complexity and management challenges (Marton et al., 2016). Unlike mixed crop-livestock systems, resource-sharing practices such as a ‘straw-for-muck’ exchange require no major changes to farming practices or land use and showed slightly higher mitigation potential. This suggests that enhancing resource flows between specialised farms may be a more effective emissions reduction strategy than on-farm integration, though further research is needed.

Anaerobic digestion (AD) of manure achieved substantial farm-level emission reductions but was not cost-effective on individual farms. Increasing digester capacity improves viability (Eory et al., 2015), pointing to opportunities for centralised AD plants (Lyng et al., 2018). The feasibility of AD is highly dependent on policy incentives, as the technology often requires substantial upfront investment and ongoing operational support. In the UK, past subsidies such as the Feed-in Tariff (FiT) and Renewable Heat Incentive (RHI) were key drivers of AD adoption (Ackrill and Abdo, 2020), but their withdrawal has slowed deployment, underscoring the technology’s dependence on supportive policy. Future policy is expected to focus on replacing the current Green Gas Support Scheme (GGSS) with a long-term framework that enhances access to capital and revenue stability, for example through the Renewable Transport Fuel Obligation (RTFO) and food waste AD mandates (DESNZ, 2024b). Wider barriers and potential environmental trade-offs such as transport infrastructure and land use change for purpose-grown crops must also be considered (Styles et al., 2022).

Some circular practices involved recycling by-products from the wider food-waste system, such as using biosolids as fertiliser and brewers’ grains as feed. These practices could have greater mitigation potential than reported, as they offset emissions from alternative waste management methods like landfill (Elgarahy et al., 2024) or composting (Assandri et al., 2021). Diversion of such products to animal feed have been shown to consistently achieve more GHG mitigation than to use them as feedstock for AD (Styles et al., 2022). Expanding assessments to the regional scale could better account for spatial factors such as land use, resource availability, transportation and infrastructure, which can affect the overall sustainability and cost-effectiveness of these practices.

4.4. Limitations

This study has several limitations. Circular practices were assessed individually, preventing an aggregated estimate of their total mitigation potential due to possible interactions and incompatibilities. Farmers likely adopt combined practices, and future work could evaluate the effects of such scenarios. For instance, the combined use of solid–liquid separation and AD has not been fully quantified. Holly et al. (2017) suggest that digestion followed by separation may reduce CH_4 emissions but increase N_2O emissions, resulting in no net GHG benefit compared with individual practices. While separation of digestate can also lower ammonia (NH_3) emissions during storage (Holly et al., 2017), further work is needed to assess these trade-offs and overall effectiveness.

Assumptions about resource flows, emission reductions and adoption costs—though based on the best available knowledge and expert opinion—introduced uncertainty. Future research could address this by incorporating sensitivity analyses. Excluding carbon sequestration potentially underestimated the contribution of circular practices. Future work incorporating farm-level soil measurements could help quantify the effect of circular practices, though the context-specific nature of sequestration makes generalisation uncertain. Direct comparisons with other UK MACCs were constrained by differences in evaluated mitigation options, with limited prior studies specifically assessing the efficacy of circular practices.

All costs and changes in N balances were attributed solely to GHG mitigation, without accounting for co-benefits or trade-offs, such as impacts on NH_3 emissions or nitrate (NO_3^-) leaching. We did not explicitly model other important N loss pathways (volatilisation, leaching, denitrification), which may have revealed further effects not captured in this study. Future research should integrate a fuller representation of N cycling to enable a more comprehensive assessment of both N balances and associated N_2O emissions. A high ranking for cost-effectiveness or N efficiency does not necessarily indicate broader environmental or economic advantages. Some lower-ranked measures may still offer valuable benefits, such as the land application of recycled biosolids improving soil health (Ippolito et al., 2021) and P cycling (Schoumans et al., 2015) to reduce the need for P fertilisers.

To optimise policy development and minimise trade-offs, future research could explore multi-pollutant MACCs (Eory et al., 2013) or LCA approaches, as demonstrated by Møller et al. (2023) and Rigamonti and Mancini (2021). Despite these limitations, this study provides a structured framework for evaluating the role of circular farming practices in GHG mitigation, improved N use efficiency and farm profitability across different farming systems.

5. Conclusions

This study makes an important contribution as the first to incorporate N efficiency into a MACC framework, extending analysis beyond cost-effectiveness alone. By linking GHG mitigation with nutrient management, the approach highlights circular practices that can deliver multiple benefits and mitigate trade-offs, offering policymakers and practitioners a more holistic evidence base to support the transition towards sustainable and resilient farming systems. The effectiveness of circular practices varied by farm type and farmer priorities. For mixed farms, alternative feed ingredients were most cost-effective, reducing GHG emissions by 4.7% while saving £200 Mg CO_2e^{-1} yr^{-1}. In dairy systems, solid–liquid slurry separation reduced emissions by 4.8%, saved £129 Mg CO_2e^{-1} yr^{-1} and lowered the N balance by 17 kg N Mg CO_2e^{-1} yr^{-1}. For arable and beef-sheep farms, cover crops and multi-species leys delivered the greatest benefits. Anaerobic digestion reduced emissions substantially (up to 7.8%) and improved N efficiency but was not cost-effective at the farm level. System-based practices such as mixed crop-livestock systems (1.2% reduction) and resource sharing (1.6%) showed greater regional mitigation potential. This comparative assessment of GHG mitigation and N efficiency provides a novel perspective for integrating climate and nutrient management strategies. The findings indicate that policy instruments should prioritise regional mitigation potential rather than prescribing specific measures or technologies.

Policy support will be critical to realise these benefits. Circular practices could deliver modest but meaningful GHG reductions, with effectiveness varying by farm type and scale, and should therefore complement other mitigation strategies. Their adoption could be incentivised through policies that recognise wider benefits—particularly improved N efficiency, reduced input costs, and enhanced farm resilience—while integrating LCA alongside MACCs to better capture environmental and economic trade-offs. Framing circularity as a practical entry point towards wider mitigation could broaden farmer engagement and accelerate progress towards net zero agriculture.

CRediT authorship contribution statement

Ffion Evans: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **James Gibbons:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Sophie Wynne-Jones:** Supervision. **Prysor Williams:** Writing – review & editing, Supervision, Conceptualization. **Dave Chadwick:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2026.110370.

Data availability

Data will be made available on request.

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