PATHWAYS TO
DAIRY NET ZERO.

IN COLLABORATION WITH

trouw nutrition
a Nutreco company

MORE MILK, BETTER MARGINS, LOWER EMISSIONS

The business and climate case for optimising animal nutrition in dairy systems



NOVEMBER 2026



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GOAL

The goal of this paper is to describe and explain the role of optimal nutrition in maximising productivity and profitability and minimising greenhouse gas (GHG) emissions from dairy systems worldwide. This paper also provides context and the underlying evidence for a high-level brief for policy makers.

AUDIENCE

The primary audiences for this paper and the policy brief are senior leaders in dairy processing companies, feed companies and advisors, and farmers. We believe regulators, policy makers and non-governmental organizations (NGO) and funding organizations will find value in this analysis as well.

WHAT IS OPTIMAL NUTRITION?

Optimal nutrition in this context is achieving the nutritional status in dairy animals – from calves, through heifers, to cows in all stages of their productive lives – in which productivity (i.e. the efficiency of use of all inputs, including feed) and profitability are maximised over the dairy animal's lifespan, and GHG emission intensity (EI, kg CO_2 eq. per kg milk) is minimised. Achieving optimal nutrition requires the most effective and efficient sourcing, production, formulation and presentation of feed, taking full advantage of available knowledge, socio-economic and agroecological resources, and being mindful of diverse objectives in different dairy systems.

SCOPE

Following Pathways to Dairy Net Zero (P2DNZ) principles, the paper includes all dairy systems, globally. The approaches discussed are general, though the details of their importance and implementation will vary across systems. The paper takes a lifecycle assessment (LCA) approach, including all aspects of dairy production related to optimal nutrition. An LCA approach considers dairy nutrition on the farm, as well as activities upstream and downstream. On-farm activities include ration formulation and feeding practices, forage production and management, forage quality, feed processing, precision feeding and use of supplements and additives. Upstream activities relate, for example, to land use change (LUC), soil management, fertiliser use and feed crop yield and quality. Downstream activities tend to be less directly related to nutrition but do include circular bioeconomy linkages such as nutrient recycling and energy recovery from waste.

BACKGROUND AND RATIONALE

Optimising nutrition in dairy systems improves milk output over the lifetime of a cow, improves overall economic viability and lowers GHG EI. In an optimised system, more milk can be produced from the same or fewer animals, reducing emissions per unit of milk and potentially reducing absolute emissions, depending on the growth of production. In all dairy systems, there are strong economic and environmental cases to optimise the nutrition of dairy herds.

Access to sufficient high-quality feed and its efficient presentation to dairy cattle are widely recognised as major constraints to improving productivity (e.g. Thornton 2010; Baltenweck et al. 2020). However, despite considerable research and development efforts, achieving sustained improvements in animal nutrition has proven challenging, particularly in emerging dairy systems (Baltenweck et al. 2020).

ECONOMIC CASE

Feed is widely recognised as the major variable cost in livestock enterprises. While feed's share of variable costs differs among dairy systems, some industry reports suggest feed accounts for around 70% in advanced dairy systems.[1] Feed conversion efficiency – the ratio of milk output to feed intake – is an important component of productivity, and even modest improvements in feed efficiency have considerable potential to improve profitability.

Whole-farm analyses of British dairy systems, for example, estimate that a 10% improvement in feed efficiency can increase gross margins by over 7%.[2] Such improvements, however, may also require investment in feeding systems: fixed costs that need to be recovered over time.

Improved feed processing, such as optimising particle size, improves digestibility and can increase milk yields by 5-10% from the same quantity of feed, increasing feed efficiency by 3-7%.[3]

Precision feeding and formulation systems are based on universal principles. These involve closely matching nutrient supply to animal requirements, improving feed conversion efficiency and milk quality while reducing unnecessary nutrient inputs and waste (Akintan et al. 2025).

In Tanzanian dairy systems, simulated 'improved feeding practices', including feed conservation, the addition of high-quality forages to diets and concentrate feeding,

[1] https://ahdb.org.uk/dairy/milk-to-feed-price-ratio
[2] https://ahdb.org.uk/whole-farm-feed-efficiency-wffe
[3] https://murska.fi/en/news/how-does-improved-feed-digestibility-translate-to-financial-benefits-for-farmers

combined with crop yield improvements, allowed sector growth targets to be met primarily through increased productivity (Hawkins et al. 2021). The models indicated that better feeding would increase milk yields by up to 60%.

Multi-objective optimisation models show that ration adjustments, such as increasing concentrate use at higher stocking densities or improving the quality of forages, can increase economic returns per cow and per hectare by increasing productivity (Notte et al. 2020).

CLIMATE CASE

In Hawkins's (2021) simulation studies discussed above, as well as increasing milk yields by up to 60%, better feeding reduced EIs by up to 38% in farms with improved cattle, and up to 52% in the low-yielding traditional dairy systems.

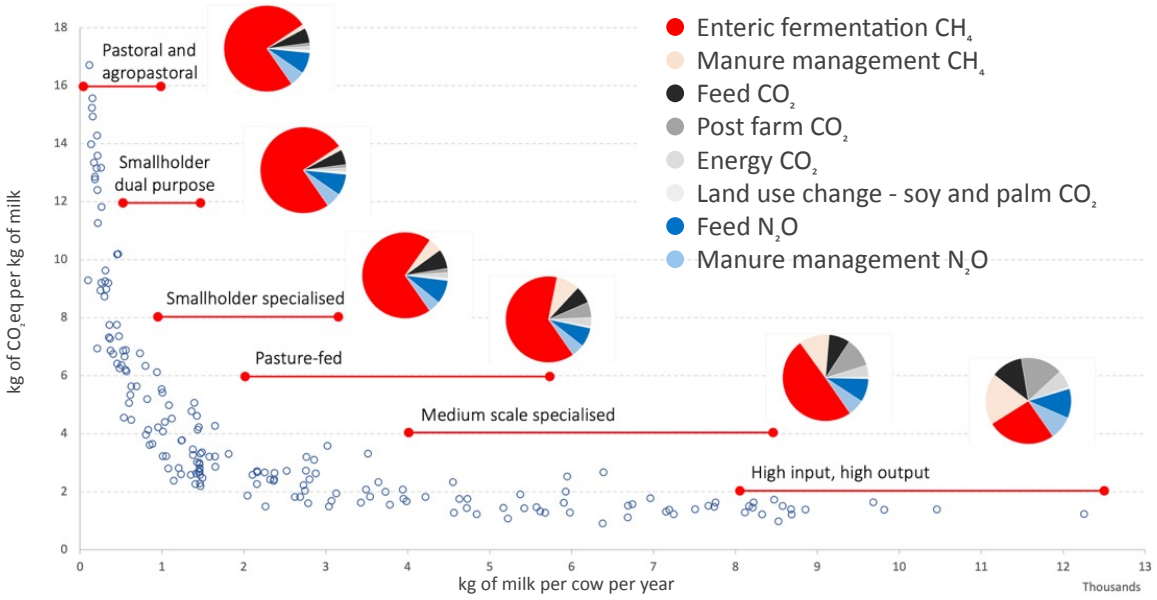
These effects were achieved largely through dilution of maintenance emissions. Feeding strategies that increase productivity and feed efficiency reduce the intensity of methane and nitrous oxide emissions, even where total farm emissions remain stable or increase slightly (Hawkins et al. 2021).

Analyses underpinning national and regional GHG inventories (e.g. Moxey and Thomson 2021) identify improved ration digestibility, better forage quality, and strategic concentrate use as cost-effective mitigation options in dairy herds. Comparative studies of dairy systems suggest that balancing pasture intake with strategic supplementation to optimise milk production can result in some of the lowest GHG EIs.[4]

High-quality, nutrient-dense feeds and targeted feed supplements can reduce enteric methane emissions while improving feed efficiency. This positions feed optimisation as a key Scope 3 mitigation approach for buyers of milk and dairy ingredients.[5] Selecting feed ingredients with lower carbon footprints can further reduce EIs while maintaining high-producing cows (Managos et al. 2025). Improving yields, particularly in emerging dairy systems, is the crucial first step to reducing EI, and optimising nutrition is central to that. Figure 1 shows the relationship between EI and milk yield (FAO 2019). Each point on the graph represents a country, with dairy emissions estimated using the FAO global livestock environmental assessment model (GLEAM[6]) and average yields estimated from FAOSTAT data.[7] Dairy EIs are highest in countries with low average productivity (to the left of the graph) and decrease rapidly as yields increase, following a characteristic 'hockey stick' pattern. This relationship between EI and yield has been observed in several other studies, including FAO (2013a); Garg et al. (2016); and Habib and Khan (2018). Figure 1 confirms that even small yield increases in the systems to the left of the graph can have a dramatic impact on EI, emphasising the priority for action in the low-yielding, emerging dairy systems.

[4] https://cias.wisc.edu/wp-content/uploads/sites/194/2019/03/ciasrb101final.pdf
[5] https://www.sustain-cert.com/news/using-value-chain-interventions-to-cut-scope-3-emissions-in-dairy-farming
[6] https://www.fao.org/gleam/en/
[7] https://www.fao.org/faostat/en/#home

FIGURE 1. Relationship between average emission intensities of greenhouse gases from national dairy systems (each point represents a country) and average productivity, estimated as fat- and protein-corrected milk (FPCM), of those dairy systems. Superimposed are the relative positions of six broad dairy systems – showing the sources of greenhouse gas emissions for each. Source: Adapted from FAO (2019).



ACCOUNTING FOR DIVERSE DAIRY SYSTEMS

Dairy production is carried out in diverse systems, illustrated in Figure 1, reflecting different combinations of agroecological conditions and socioeconomic factors. Extensive dairy production occurs in pastoral and agropastoral systems, in which milk can be the main source of household protein. Dairy farming is common in labour-intensive systems, usually as part of a mixed farming system. Dairy cattle in these systems may be dual purpose, or may be specialised, as typified by the smallholder dairy producers of the East African highlands and South Asia. Dairy farming is also carried out with greater intensity in specialised high-input, high-output systems. Different systems have different objectives, face different constraints and are presented with different opportunities for development. Systems vary greatly in their baseline milk yields and GHG emissions (Figure 1) and will necessarily follow different pathways towards improved productivity and anticipated reductions in EIs.

Figure 1 reflects this diversity, with the relative positions of different dairy systems[8] superimposed on the graph and their relative sources of emissions indicated in pie charts. Enteric methane contributes a far greater share of emissions in the less productive systems. As system productivity increases, the relative contribution of enteric methane diminishes, and the share of emissions associated with manure management, feed production and energy use increases.

The nutritional status of dairy cattle varies across these systems, and options available to optimise nutrition are equally diverse. This is particularly apparent in the differences between dairy systems in mid- to high-income settings – with established feed supply, infrastructure and management capacity – in contrast to dairy systems in low-income settings, where seasonal feed scarcity, insufficient intake and limited water access may be primary constraints. For dairy systems in low-income settings, the priority is often to ensure a sufficient provision of feed and water, rather than to optimise productivity. These basic provisions can still have a dramatic impact on EI. The higher yielding, more advanced dairy systems of mid- to high-income economies generally have more developed support systems, such as input suppliers, advisory capacity and customer incentivisation. There is still scope for improvement in these systems, however, which should be able to move faster, perhaps towards different targets, with a greater proportional focus on N_2O and CO_2 reductions, for example.

In low-income systems, livestock often play a role as a substitute for social and economic infrastructure. Animals function as savings, insurance and providers of draft power, fuel and social capital (Otte et al. 2012), creating incentives to maintain larger herds even when feed and water resources are limiting (Tricarico et al. 2020). This dynamic contrasts with the principles of optimising nutrition that apply to more developed dairy systems – to maintain fewer, more productive animals – and drives structural overstocking and chronic undernutrition in cattle. Reducing animal numbers and increasing per-animal productivity is not always a technical decision. In many low-income systems such decisions are constrained by risk management and institutional gaps.

[8] The six systems shown in Figure 1 were developed in a scoping study for the P2DNZ initiative.

FIVE LEVERS TO OPTIMISE NUTRITION

While similar principles apply across dairy systems, optimising nutrition requires approaches tailored to local conditions and production characteristics. The relative importance of different interventions will vary depending on the feed resources available, the prevailing agroecological and socioeconomic circumstances, and the objectives of each production system. The priority in every case is to make the most effective use of available resources to improve productivity and profitability while reducing greenhouse gas emissions.

While most mitigation approaches are compatible, their GHG reduction potential may vary because of interaction effects. Implementing compatible mitigation bundles requires careful consideration of their interactions, economic viability, and how well they integrate with existing farming systems (Kankanamge et al. 2025). Five levers to optimise nutrition are discussed below.

1. IMPROVED FEEDING PRACTICES



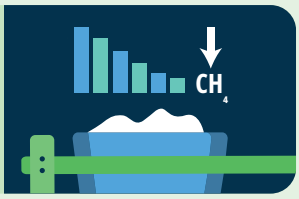
2. FORAGE AND PASTURE MANAGEMENT



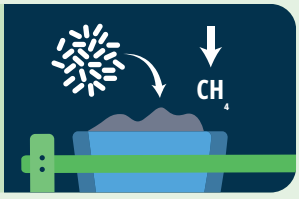
3. LIVESTOCK MANAGEMENT



4. LOWER-EMISSIONS FEED



5. METHANE-SUPPRESSING FEED SUPPLEMENTS



1. IMPROVED FEEDING PRACTICES



Improved feeding practices are at the centre of feed optimisation in dairy systems. Feeding improvements reduce EI rather than always reducing total emissions. If cows produce more milk from the same or fewer inputs, EIs fall, even if absolute emissions may remain similar or rise due to more production overall (FAO 2013a).

Better feeding also reduces upstream emissions by improving the efficiency of feed production, and downstream emissions by lowering waste. When diets are better balanced, less nitrogen is excreted, which can reduce ammonia and N_2O losses from slurry and manure handling (Hristov et al. 2013b).

SUFFICIENCY

The literature shows that in many of the emerging dairy systems the first intervention is not optimisation but sufficiency: securing enough feed and water (Tricarico et al. 2020). In low-management, range-based, and smallholder systems, practical, nutrition-relevant interventions include providing ample, clean drinking water; increasing feed offered per animal; improving feed quality; securing dry-season feed supply; and improving the use of crop residues. Providing sufficient nutrition to dairy animals may also involve some of the levers discussed below, such as strategic supplementation and aligning herd size with resource availability. These systems are far to the left of the graph shown in Figure 1, where even tiny increases in yield can result in dramatic reductions in EI.

PREPARATION AND PRESENTATION

Smarter ration formulation and presentation are crucial in dairy nutrition because they determine whether cows receive the right nutrients, in the right amounts, at the right intake level, and in a form they can efficiently eat and digest. These are important steps towards improving feed efficiency and reducing EI. Chopping, mixing, ensiling and careful conservation of feed avoid spoilage and reduce refusals, both of which lead to waste. Good preparation improves digestibility and increases nutrient availability, supporting better feed conversion efficiencies.

Presentation of feed is also important because the physical form and timing of feed provision influence intake, rumen function and the balance between energy and protein supply. When cows eat a more consistent, well-formulated ration, less nitrogen is wasted and less methane is produced per unit of milk (Aguerre et al. 2011).

In practice, feed preparation and presentation should be closely linked to high-quality forage production, considered ration balancing, reduced feed losses and the optimal use of low-emission feed sources. These measures interact to improve both productivity and EI.

OPTIMISED FEEDING THROUGHOUT THE ANIMAL'S LIFE

Optimised feeding throughout the life of the dairy animal plays an important role in building dairy systems that are both productive and lower in GHG emissions. There is strong evidence for the benefits of optimising nutrition not only in milking cows, but throughout all stages of their production cycle (National Academies of Sciences, Engineering, and Medicine 2021). With a two-year lead-up to the first lactation, it follows that extending the productive lifespan of dairy cows can reduce the intensity of emissions over a cow's lifespan and improve the profitability of dairy production (Grandl et al. 2019). Based on an optimisation of the total cost of maintaining herd structure in an advanced dairy system, the sum of five drivers (genetic opportunity cost, herd replacement cost, lack of maturity cost, aged cow cost, and calf value opportunity cost), DeVries (2020) estimates the optimal productive lifespan to be five lactation cycles. The optimal productive lifespan will vary, however, depending on productivity (Gazzarin et al. 2025) and system, and may not always be dominated by economic considerations.

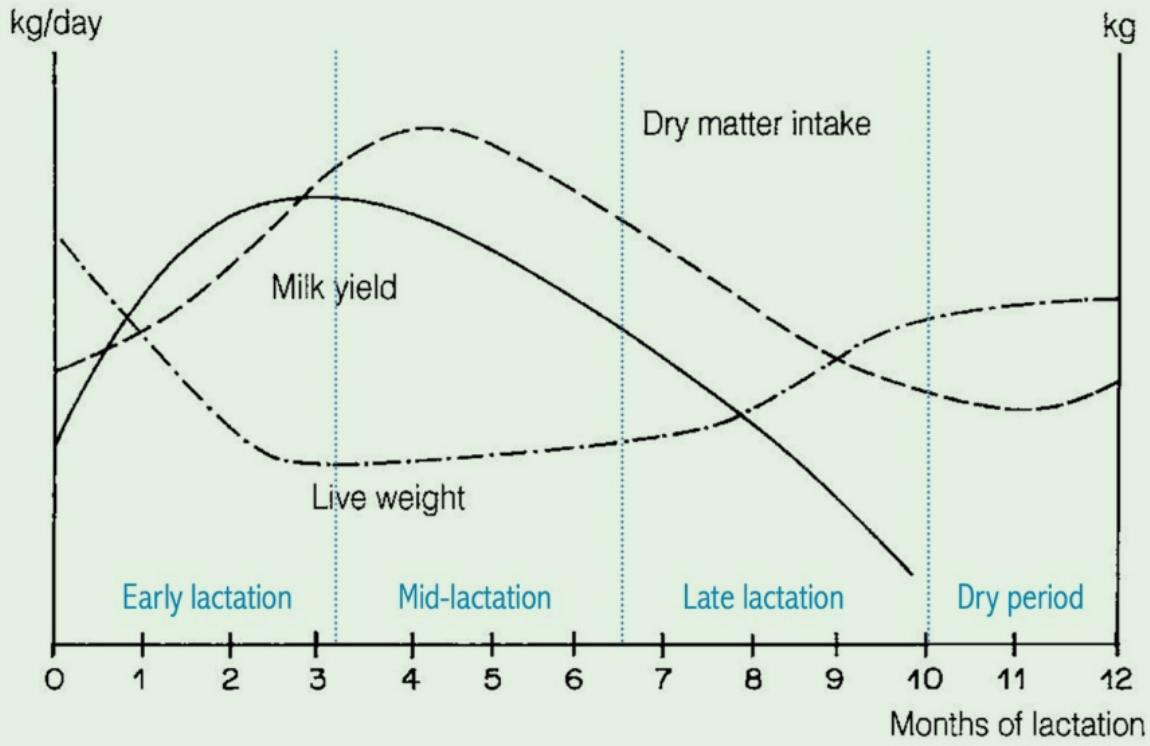
The role of feeding begins at birth (Dong et al. 2019) and the beneficial impacts of feed interventions in calves may persist into later life stages (Meale et al. 2021). Feeding more nutrients to pre-weaned calves has been shown to improve later-life productivity. Leal et al. (2025) observed that calves fed more nutrients grew faster before weaning, produced more milk and milk fat in their first and second lactations, and showed better fertility.

The nutrient-enhanced diet also improved longevity, because the risk of being culled before later calvings was roughly halved compared with calves given a more restricted diet.

Heifer studies show that higher-quality diets and feeding levels that support efficient growth can improve feed efficiency and reduce methane EI, helping animals reach breeding and calving targets earlier. Earlier calving shortens the unproductive rearing period and can increase lifetime milk yield and reduce emissions associated with raising replacements. For newborn calves, good intake of quality colostrum in the first 24 hours of life is critical to get them off to a good start. Health links are important here to avoid losses due to calf diarrhoea and pneumonia. Feed requirements change from the post-colostrum period to weaning, during weaning transition, and for weaned heifers. During the weaning transition, for example, it is important to encourage rumen development, and for heifers, it is important to support steady skeletal growth, rather than rapid fat gain.

Dietary needs vary not only during the major life stages of the dairy cow, but also during each lactation cycle, as illustrated by the 'lactation curve', shown in Figure 2. In lactating cows, diets formulated around production stage and actual requirements can improve milk output per unit of feed and reduce EIs.

FIGURE 2. The lactation curve of a dairy cow, showing dry matter intake, milk yield and live weight changes during her lactation cycle. Source: Adapted from Holstein Foundation (2017).



Across all stages of a dairy cow's productive life, and of the lactation cycle, each phase has very specific nutritional requirements, which should be matched by the feeding strategy to optimise nutrition. Matching feed provision with nutritional requirements through all stages of growth and production, and monitoring those responses, is at the core of precision nutrition, the subject of the following section.

RATION FORMULATION

Ration formulation in dairy feeding is the process of building a diet that meets a cow's nutrient needs for maintenance, milk production, pregnancy and body condition while keeping feed cost low and the ration both palatable for the cow and practical to feed. It also involves making the most of what is available, such as responding to changing fodder quality, or adapting the formulation to take advantage of a new feed that becomes available. In practice, it means choosing the right mix of forages, concentrates, minerals, and supplements, then balancing energy, protein, fibre, minerals, and vitamins against the cow's requirements.

By matching nutrient supply to animal requirements, 'precision nutrition' raises feed efficiency and cuts avoidable losses of nitrogen and energy. There are two dimensions to precision nutrition: the first is recognising variations in nutrient requirements and responses between individual animals, and the second is recognising changes in nutrient

requirements and responses over time. In practice, this means formulating and delivering nutrition to smaller units, be they groups within herds or individuals within groups, and changing formulations more frequently over time.

Precision nutrition in dairy cows delivers climate benefits mainly by cutting enteric methane per unit of milk and by reducing nitrogen losses (and thus nitrous oxide) from manure, with additional gains from improved feed efficiency and lower upstream emissions from feed production.

Precision nutrition involves several tactics: better and more frequent feed analysis; regular ration evaluation and reformulation; staged feeding; monitoring intake and milk output; and targeted use of additives (e.g. Dalmonte et al. 2026). At the same time, precision feeding reduces surplus protein, which lowers nitrogen excretion and helps curb ammonia and nitrous oxide losses from manure (Morey et al. 2023). The evidence is encouraging but also reveals possible trade-offs.

A controlled study of precision feeding in grouped dairy cows found lower ammonia-related indicators in manure, but an increase in methane and carbon dioxide from stored manure (Morey et al. 2023). The benefits depend on the full feeding and manure management system, not just the ration itself, so precision nutrition works best as part of an integrated strategy that also considers animal health, cow fertility, forage quality, milk yield, manure management and the selective use of additives where appropriate.

Precision feeding requires accurate data, and there are several tools and resources available to capture them and help balance rations correctly. Automated feeding systems for individual cow delivery can also be integrated into the production system, where feasible.

There are, of course, practical challenges and costs associated with delivering more precise nutrition. For example, there may be increased requirements for labour or technology to manage multiple groups of animals, capital costs associated with equipment to supplement individual animals with concentrate, and indeed the actual costs of ingredients. These factors need to be accounted for in the context of the production system to determine the optimal level of precision.

IMPROVING FEED MATERIALS

Improving the quality of the feed materials themselves is often one of the most practical mitigation routes. Higher-digestibility forages, better grass management (see below), earlier-cut silages, better-preserved feeds and improved forage varieties can all increase energy intake and milk output while reducing methane intensity (FAO 2013a).

Improving forage quality, digestibility and ration balance can lower dairy GHG emissions by improving feed efficiency and reducing enteric methane intensity. Eugène et al. (2021), for example, show that methane yield decreases as forage digestibility increases, and that forage type is also important: grasses, legumes and maize differ in their effects on methane and overall GHG emissions.

Rivera Moncada et al. (2025) have shown that, in the context of animal emissions, improving diet digestibility is one of the most effective strategies for reducing all types of direct GHG EI. In a sensitivity analysis, diet digestibility (based on dry matter) emerged as the most sensitive parameter when estimating direct animal emissions using GLEAM (see footnote 7). Rivera Moncada et al. (2025) found diet digestibility to have a sensitivity index close to –3, indicating that a 1% increase in diet digestibility would result in an approximately 3% reduction in EI.

2. FORAGE AND PASTURE MANAGEMENT



Well-managed forage crops, including grass, can increase milk yield per hectare, improve forage quality, reduce fertiliser-related N losses, increase nutrient recycling and facilitate increased soil carbon capture. Evidence from pasture-based dairy studies shows that intensifying grazing systems, when done carefully, can increase milk output and create a land-saving effect, freeing land for carbon sequestration or other productive uses (Oliveira et al. 2022; Delaby et al. 2020).

While many GHG benefits are available from pasture management, it is important to avoid trade-offs. For example, reducing a short-lived GHG (CH_4) at the expense of increases in persistent GHGs (CO_2 and N_2O) should be avoided, calling for a separate consideration of the individual gases involved (Mazzetto et al. 2025). Mitigation actions that lower milk yields per hectare may also have trade-offs, for example if such a production shortfall were compensated for by increasing the dairy area through detrimental LUC. Understanding such trade-offs is essential if they are to be managed.

There are also important interactions among milk yields, pasture quality and the use of dietary supplements that need to be balanced (Soder and Brito 2023). EI can be kept low by producing grass with few inputs, or by increasing milk yields through targeted use of fertiliser on pasture. High EIs often result from low to intermediate milk yields from grass with untargeted, sporadic inputs combined with the use of high-emission concentrates to increase milk yields.

OPTIMISING GRAZING

Extending the grazing season and improving grass utilisation can reduce emissions because cows eat higher-quality forage, need less conserved feed, and generate less slurry than during housing. For Irish dairy cattle, for example, it has been estimated that each extra 10 days at grass can cut GHG emissions by about 1.7% (Teagasc and Board Bia 2019). While this holds for a spring-calving model, practised extensively in Ireland and New Zealand, the details may vary for other grazing systems, for example where the grazing period tends to

be shorter and use of supplementary feeds, including buffer feeds, generally higher. Each system needs to be optimised according to its characteristics.

Rotational grazing, tighter control of stocking rate and maintaining pasture at a high nutritive value can improve feed intake and milk production while reducing EIs. Integrating legumes such as clover can also lower emissions by reducing reliance on synthetic N fertiliser while sustaining productivity (Weggler et al. 2025; Cashman et al. 2026). Better-quality pasture supports faster growth, higher milk yield and shorter production cycles, spreading emissions over more output. However, the benefits depend on matching grazing pressure, fertilisation and pasture growth to local conditions; poorly managed intensification can increase nitrogen losses and degrade pasture, reducing the persistence of the sward, potentially reversing the beneficial effects of carbon sequestration.

FORAGE CONSERVATION

Forage conservation underpins year-round dairy feeding by stabilising the supply of digestible energy and fibre, thereby supporting high milk yields while influencing GHG emissions through enteric methane and conservation losses. Meta-analyses show that improved forage quality, achieved by harvesting at earlier maturity and conserving rapidly under anaerobic conditions, increases daily milk yield and reduces methane EI because more digestible diets raise feed efficiency and dilute maintenance energy costs (Arndt et al. 2022; van Gastelen et al. 2019; 2026). At the same time, fermentation quality and dry-matter losses during ensiling affect the energy density of the ration and the substrates available for rumen methanogenesis, so poor conservation can erode both productivity and emission benefits (Krueger et al. 2023).

The type and form of conserved forage further modulate methane outcomes. Replacing part of a grass-silage diet with corn silage typically increases energy density and dry-matter intake, often lowering methane EI while maintaining or improving milk protein, although effects on milk fat and total yield depend on overall ration balance (van Gastelen et al. 2026).

Conversely, high-quality fresh grass from unrestricted grazing can achieve very low methane EI early in the season compared with grass-silage-based indoor feeding, but conserved forages remain essential when pasture growth is limited, making strategic combinations of grazing and silage key to optimising both yield and emissions (Cromheeke et al. 2026).

In practical terms, optimising forage conservation for low-GHG, high-yielding dairy systems requires harvesting at optimal maturity, rapid wilting and sealing to minimise aerobic losses, and ration designs that balance starch from corn silage with effective fibre from grass or legume silages. Where feasible, integrating part-time grazing with well-conserved silage can maintain high milk output while reducing methane EI relative to fully indoor, silage-based feeding. Accounting for silo-phase GHG emissions in carbon footprints would ensure that conservation choices are evaluated against their true climate impact alongside enteric and manure emissions (Krueger et al. 2023).

AVOIDING LAND USE CHANGE

Dairy emissions from LUC arise when land is converted or managed differently to support dairy production – most commonly when forests, savannahs, or other natural ecosystems are turned into pasture. Such land conversion releases large stores of carbon held in vegetation and soils, mainly as CO_2 (and some N_2O), creating a "carbon debt". However, direct forest clearance to graze dairy cows is rare compared to that associated with beef production. Most dairy farming uses established pastoral land or intensive indoor feeding. More important is avoiding conversion of grassland to arable land. Maintaining permanent grassland is itself a mitigation measure, especially where conversion to arable land would release soil carbon or reduce long-term sequestration potential. Reviews of grassland carbon storage conclude that avoiding conversion of grassland to arable use, reducing overgrazing, and keeping productive permanent pasture in place are among the more robust ways to protect stored carbon (e.g. Jordon et al. 2024).

LOW-CARBON FERTILISER

The use of low-carbon fertiliser is covered below, in the context of feed production. Since fertiliser is also used routinely in managed dairy pasture systems (Hemingway 2000), the same arguments apply here. This section focuses on the use of manure as a low-carbon fertiliser.

Because of the proximity of pasture to dairy cattle, the return of manure to pasture is particularly relevant, and is important both as a means of disposing of manure and as a source of fertiliser. Manure can be an effective low-emission fertiliser for dairy pastures when it is managed to maximise nutrient use and minimise GHG and ammonia losses.

It supplies nitrogen, phosphorus, potassium and organic matter, improving soil fertility and supporting pasture growth while recycling nutrients produced by the dairy herd.

To reduce emissions, slurry should be applied at rates that match nutrient demand, during cool and moist conditions, and incorporated into the soil where practical. On established dairy pasture, low-emission spreading methods such as trailing shoe or shallow injection systems place manure close to the soil surface beneath the pasture canopy, reducing ammonia volatilisation and N_2O emissions, compared with splash-plate spreading. Avoiding application before heavy rainfall also helps reduce nutrient runoff and N_2O emissions.

Regular slurry testing and nutrient budgeting allow farmers to reduce reliance on synthetic N fertilisers, lowering the carbon footprint of pasture production. When combined with effective grazing management and healthy soils, well-managed manure applications can recycle nutrients, support pasture productivity and reduce dependence on manufactured fertilisers (SAI Platform 2022). While this can contribute to the sustainability of dairy farming, the environmental outcome depends on application rate, timing, soil conditions and associated ammonia, nitrous oxide and methane losses (Silva et al. 2025).

Urease inhibitors and nitrification inhibitors mixed with the manure before application to pasture or sprayed onto the soil can enhance the use of manure. By slowing the release of nitrogen, inhibitors can reduce losses to the environment through ammonia volatilisation and GHG emissions. As a result, nitrogen use efficiency in pasture production increases, reducing the need for synthetic fertiliser application.

IMPROVED PASTURE NITROGEN USE EFFICIENCY

Improving nitrogen use efficiency in pasture production reduces the amount of reactive nitrogen lost through N_2O emissions, nitrate leaching and ammonia volatilisation, while also lowering the need for synthetic N inputs. In practice, this is usually achieved through better fertiliser timing and rate, matching N supply to pasture demand (Powell et al. 2010). The use of clover or other legumes is another important strategy to reduce the need for synthetic fertiliser inputs.

AGRONOMY AND CARBON SEQUESTRATION

Well-managed grasslands can store carbon in soil, especially when management practices increase root inputs and reduce soil disturbance. Measures commonly linked to higher sequestration include maintaining permanent pasture, reducing tillage, improving sward persistence, moderate intensification of nutrient-poor pasture and converting some grass leys to grass-legume mixtures. The potential is real, but it is not unlimited. Reviews suggest grassland carbon sequestration can materially improve the GHG balance of ruminant systems, and reported offsets from pasture sequestration can reduce dairy footprints by a noticeable amount in LCAs; however, sequestration rates vary widely and tend to slow as soils approach a new equilibrium (Soussana et al. 2010).

As well as below-ground sequestration of soil organic carbon, dairy pastures also sequester carbon above ground, where carbon is stored in living biomass such as perennial grasses, legumes, hedges, and trees – particularly in silvopastoral systems (Brook et al. 2022).

Carbon sequestration in dairy pastures has the potential to make an important contribution to reducing the net climate impact of dairy production. While methodologies exist to measure and account for sequestered carbon (e.g. IDF 2022), their application is not yet widespread, and mechanisms to recognise and reward carbon sequestration remain limited. Developing credible and practical approaches to accounting for soil carbon sequestration, and creating appropriate incentives for farmers, will be important to realising this potential.

3. LIVESTOCK MANAGEMENT



Livestock management, as it relates to feeding, is a major lever for improving dairy productivity while reducing GHG emissions because it changes the number, age structure and productive efficiency of animals in the herd. At herd level, emissions are dominated by enteric methane and, to a lesser extent, manure and upstream inputs; therefore, strategies that increase lifetime milk yield, reduce non-productive animals and shorten the rearing phase of replacements tend to reduce EI (FAO 2013a; Hristov et al. 2013a; Knapp et al.

2014). Recent simulation and LCA studies confirm that herd structure and reproduction management can deliver emission reductions without necessarily compromising output or gross margin, although the size of the benefit depends on the production system and the productivity of the starting herd (Liang and Cabrera 2015; Chen et al. 2026).

HERD MANAGEMENT

The general principle is that a more efficient herd produces more milk from a lower maintenance burden. Because each animal carries a maintenance cost in feed and associated methane emissions, improving fertility, longevity and replacement efficiency reduces the proportion of the herd that is unproductive or only partially productive at any time (Wall et al. 2012; Hristov et al. 2013a).

This is supported by modelling studies showing that better herd structure and higher milk production can benefit both the economics and emissions of milk production. Liang and Cabrera (2015) found that reducing the proportion of first-lactation cows reduced GHG emissions by 3.4 to 7.3%, while higher target milk production increased net economic returns and lowered EI. More recently, Chen et al. (2026) showed that tailored herd management strategies could reduce GHG emissions by up to 3.2% on average across herds, again with no obvious trade-off against gross margin in their high-yielding Danish systems.

Reducing the rate of cow replacement is one of the clearest herd-level strategies for lowering GHG emissions because it reduces the number of heifers that must be reared and the number of non-lactating animals carried by the system. As well as reducing the amount of feed needed per kg milk produced, and therefore cutting emissions associated with growing animals that are not yet producing milk, economic savings are made by reducing housing requirements and animal health expenses. Reducing replacement rates also increases the average age and parity of the milking herd, which usually improves milk yield per cow and lowers EI (Wall et al. 2012; Knapp et al. 2014).

Evidence from recent studies is consistent. Sommerseth et al. (2024) found that a reduced replacement rate lowered total farm emissions by up to 8% and emissions per unit of output by up to 6%. Similarly, Talukder et al. (2025) reported that reducing replacement rate lowered EI by 0.9 to 1.7 kg CO_2 eq. per kg milk solids across eight Australian case-study farms, although net farm emissions increased in some cases.

This is an important caveat: the environmental benefit is strongest when reduced replacement is accompanied by good fertility, health and longevity, rather than being achieved simply by keeping poorer-performing cows longer (Talukder et al. 2025; Chen et al. 2026).

The process of minimising the number of unproductive animals in a herd is sometimes referred to as ‘right-sizing’ the herd. An important tool in achieving this is the judicious use of sexed semen. Sexed semen yields a 90% chance of producing a heifer calf, which allows

farmers to breed high-quality replacement heifers from their top-performing cows, while using beef genetics on the rest (Holden and Butler 2018). Using sexed semen reduces feed-related emissions in a dairy herd primarily by improving herd productivity and efficiency: it increases the proportion of future milk-producing female calves while allowing the rest of the herd to be bred to beef sires. This shortens the time animals spend in the system unproductively and lowers the total feed required per unit of milk or indeed meat produced (Beck et al. 2026). Overall system emissions can also be reduced as producing beef from the dairy herd is highly efficient (van Selm et al. 2021).

An important approach to save on feed and labour costs is to consistently identify and remove animals that do not meet performance targets. Careful monitoring of growth in youngstock helps ensure they begin calving at the right size and age, avoiding undergrown heifers that fail to perform.

Right-sizing often means optimising herd numbers to fit production levels and aspirations and adjusting the heifer inventory to that required to maintain the milking herd. Technology can help with maintaining good records on performance and genetics to ensure replacements are bred from the best animals. This important aspect of herd management can help ensure that the best possible results are obtained from optimising the nutrition of the herd.

Earlier age at first calving (AFC) improves productivity because heifers enter the milking herd sooner and spend less time in the costly rearing phase. This reduces the number of days before first milk production, shortens the feed and management burden of replacements, and can reduce emissions per unit of milk produced over the animal's lifetime (Wall et al. 2012; FAO 2013a). In practical terms, a lower AFC means a greater share of farm resources is directed towards productive cows rather than growing replacements.

AFC is closely linked to both emissions and economics, provided heifers calve at a suitable body size so that subsequent performance is not compromised. Baker et al. (2020) reported that lowering AFC was among the key management options for reducing net emissions on a typical UK dairy farm, alongside replacement rate adjustments and other herd measures. In the Norwegian study by Sommerseth et al. (2024), accelerated heifer growth had only minor emissions effects by itself, but the combination of faster growth and reduced replacement rate improved gross margins, animal health and emissions performance. This indicates that earlier AFC is best understood as part of a broader replacement strategy rather than as a stand-alone mitigation measure.

Increased milking frequency can improve productivity by increasing milk yield, but its effect on GHG emissions is more variable than that of the replacement and AFC strategies. If additional milk is produced with only a modest increase in feed intake and other inputs, EI can fall because emissions are diluted over more output. If, however, the extra milking drives higher feed use, more labour, or greater cow stress without a proportionate yield response, the emissions benefit may be small or absent (Bacenetti et al. 2016; Chen et al. 2026).

BREEDING FOR FEED EFFICIENCY

Historically, dairy breeding programmes prioritised increased milk yield. Selection for this single trait, however, often resulted in unfavourable correlated responses, including reduced fertility. This led to the development of multi-trait breeding indices that incorporate a broad range of economically and biologically important traits, including feed efficiency.

Genetic selection for improved feed efficiency is increasingly recognised as a sustainable strategy to mitigate enteric methane emissions. The use of genomic estimated breeding values (GEBVs) enables the identification of animals with superior efficiency and lower EI (Pickering et al. 2015). De Haas et al. (2021) highlight that exploiting natural genetic variation in methane emissions offers a mitigation approach that is cost-effective, cumulative, and permanent. Although substantial initial investment is required to establish reference populations and phenotyping systems, ongoing gains can be achieved at minimal additional cost once implemented.

Improvements in environmental outcomes have historically been achieved indirectly through selection for productivity traits (Wall et al. 2010). However, breeding objectives are increasingly incorporating both indirect and direct indicators of emissions. Indirect approaches include selection for feed efficiency (e.g. residual feed intake, RFI) and overall herd fitness traits such as fertility, health, and longevity, all of which contribute to reduced EI. RFI is defined as the difference between actual feed intake and expected intake based on maintenance and production requirements (Hristov et al. 2013b). Direct selection for methane emissions is conceptually attractive and gaining traction. While operational in some countries, such as Canada,[9] it remains constrained by the complexity of large-scale phenotyping (i.e. actually measuring emissions).

Genomic selection offers a practical pathway to overcome these limitations by enabling early-life prediction of breeding values without the need for direct measurement of methane emissions in all animals (Pickering et al. 2015; Fouts et al. 2022). However, robust implementation requires large, well-characterised reference populations with both phenotypic and genotypic data, necessitating coordinated international efforts.

Initiatives such as the Efficient Dairy Genome Project aim to address this need by generating data to improve feed efficiency and reduce methane emissions through genomic approaches (Richardson 2018; Schenkel et al. 2019).

As measurement technologies for methane emissions continue to advance and datasets expand, the integration of methane-related traits into routine breeding programmes is expected to become increasingly feasible. Overall, breeding for feed efficiency, in the context of the available feed resources, represents a key component of multi-trait selection strategies aimed at improving both productivity and environmental sustainability in dairy systems.

[9] https://lactanet.ca/en/genetic-selection-reduced-methane-CH_4/

CATTLE HEALTH AND WELFARE

Improved feeding only delivers its full benefit when cows are healthy enough to eat, ruminate, absorb and use nutrients efficiently. Feed efficiency, milk yield and reproductive performance are all strongly influenced by health status, because disease can reduce intake directly, alter feeding behaviour, and divert nutrients away from production towards immune and repair processes (Llonch et al. 2018; MSD Veterinary Manual 2026).

This is especially important during the transition period between late pregnancy and early lactation, where metabolic and infectious disorders are common and where small disruptions in health can rapidly erode the gains from better ration formulation and feeding management (Pawar et al. 2026). In practice, this means feeding strategy and health management are best considered together, rather than being treated separately.

The transition period is the most vulnerable point, because dry matter intake often lags behind the rapidly rising energy demand for milk synthesis.

If cows enter lactation underfed or over-conditioned, they are more likely to develop negative energy balance, ketosis, fatty liver and reproductive failure, all of which compromise the biological return from improved feeding (Mulligan et al. 2006; Overton and Waldron 2004; Pawar et al. 2026).

If cows are undernourished, they may not be able to respond to improved diets through increased milk yields unless the nutrient supply becomes sufficient to support maintenance, immunity and lactation at the same time. Low body condition and inadequate energy or protein intake reduce milk production, weaken immune function and increase disease susceptibility, creating a cycle in which poor health further depresses feed intake and performance (Fraser 2018).

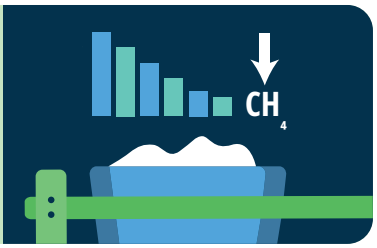
Pathogenic disease reduces the benefits of feeding by lowering intake, impairing rumen function and increasing nutrient use by the immune system. Mastitis, metritis and lameness can all reduce milk yield either directly or indirectly, for example through pain-related reductions in feeding time or by triggering inflammatory nutrient losses (MSD Veterinary Manual 2026; Llonch et al. 2018).

Good health management therefore protects feed returns. Biosecurity, early disease detection and prompt treatment reduce the “hidden” feed cost of infection and help preserve both milk output and feed conversion efficiency; this is particularly important for subclinical disease, where reduced yield may occur without obvious signs (MSD Veterinary Manual 2026).

Non-pathogenic stress factors such as heat, overcrowding, feed competition, poor flooring and inadequate resting conditions also undermine the value of improved feeding. Animal welfare issues such as these can reduce feeding time, increase feeding rate, disrupt rumen stability and increase the risk of subacute ruminal acidosis, even if the ration itself is well formulated (DeVries 2013; Llonch et al. 2018).

Stress management is therefore a feeding issue as much as a welfare issue. Ensuring adequate feed space, frequent feed access, comfortable housing and protection from thermal stress helps cows express normal feeding behaviour, maintain rumen health and capture the intended benefits of the diet (DeVries 2013).

4. LOWER-EMISSIONS FEED



Producing or sourcing low-emissions feed can maintain dairy system productivity while lowering EI. GHG emissions embedded in feed can be quite substantial and are mostly associated with LUC, the use of inorganic fertilisers and, to a lesser extent, energy use in producing, processing and transporting feed ingredients. Sourcing feeds with lower embedded emissions is particularly important when they replace low-quality forage or imported protein feeds with higher carbon footprints. Process-based modelling shows that diet changes can reduce whole-farm GHG emissions, but the benefits depend on how feed changes interact with manure management and land use (Ouatahar et al. 2024). In practical terms, low-emissions sourcing means choosing feed ingredients that avoid carbon-intensive inputs such as heavy use of synthetic fertilisers, deforestation-linked ingredients or poorly productive feed crops (Weggler et al. 2025). Selecting low carbon footprint ingredients in diet formulation can have an important impact on overall emissions (Wilkinson and Garnsworthy 2017), though care must be taken that diets be formulated to maintain or increase yield.

Access to reliable information is key to understanding the embedded emissions of ingredients being sourced. There are several initiatives that provide such information, such as the GFLI database – a compilation of feed ingredient datasets collected using an LCA methodology – available under various licensing arrangements.[10]

Local sourcing of feed in dairy production is often presented as a strategy to improve environmental performance by reducing transport requirements, with co-benefits relating to strengthening nutrient cycling and increasing farm-level self-sufficiency. The evidence, however, suggests that the benefits are conditional rather than automatic. Sasu-Boakye et al. (2014) found that localising livestock protein feed production could reduce GHG emissions in a Swedish dairy context, but this was accompanied by increased land use for feed production, highlighting an important trade-off between climate and land demand outcomes. Similarly, case-study evidence on recoupling dairy and crop production indicates that environmental gains depend strongly on how cooperation between farms is implemented and whether local resources are used efficiently (Regan et al. 2017). Overall, local sourcing may support more circular dairy systems, but its net environmental value depends on feed type, productivity, land use consequences and the broader production system.

AVOIDING LAND USE CHANGE

The LUC risks to dairy emissions have been discussed under ‘Forage and pasture management’. The same principles apply to feed crop production, though the LUC links to feed crops are generally indirect, as the products entering the dairy feed chain are usually secondary co-products of crops grown primarily for human consumption, such as soybean meal and palm kernel expeller. While LUC-associated emissions from feed production account for a relatively modest 1% of dairy emissions globally (FAO and GDP 2018), feed resources associated with LUC should be avoided.

[10] https://globalfeedlca.org/gfli-database/

LOW-CARBON FERTILISER

Synthetic nitrogen fertilisers account for 5% of total global GHG emissions, with roughly one-third from production and two-thirds from field application (Gao and Cabrera Serrenho 2023). The backbone of nitrogen fertiliser production is the Haber-Bosch process, which combines atmospheric nitrogen with hydrogen to form ammonia. Currently, some 99% of that hydrogen is derived from fossil fuels, making ammonia production responsible for up to 1.8% of global CO_2 emissions and about 2% of global energy consumption (Mingolla and Rosa 2025).

Low-carbon fertilisers aim to reduce the GHG footprint of conventional fertiliser production and use. There are several approaches to low-carbon fertiliser production that are gaining momentum. One is to produce synthetic fertilisers using renewable or low-carbon sources of energy (e.g. hydro or nuclear power, respectively). The 'green ammonia' pathway is another approach, which derives hydrogen from water electrolysis powered by renewable energy such as wind, solar or hydro power. Industry sources[11] report that a 99% reduction in GHG emissions can be achieved by switching from traditional synthetic nitrogen fertilisers to green ammonia.

Making full use of manure as organic fertiliser is another potential pathway to low-carbon fertiliser, though Gao and Cabrera Serrenho (2023) suggest that manure is currently not an appropriate substitute for synthetic fertilisers. Manure emits 1.9 times more GHGs than an average synthetic fertiliser per unit of N, largely because of additional emissions generated in manure storage and mobilisation.

Realising the full potential of manure, as part of a circular bioeconomy, requires attention to four interconnected stages: collection; treatment and storage; nutrient analysis; and application.

IMPROVED NITROGEN USE EFFICIENCY IN FEED PRODUCTION

Improving crop nitrogen use efficiency involves matching nutrient supply to plant demand, optimising soil health, and using precision application methods to reach an ideal efficiency target of 70-80%. Gao and Cabrera Serrenho (2023) suggest that increasing crop nitrogen use efficiency is the single most effective strategy to reduce emissions from feed production. Nitrogen use efficiency by feed crops can be enhanced by split applications of fertiliser, soil- and plant-based diagnostics, and the strategic use of organic manures and legumes. This means applying carefully formulated fertilisers only when feed crops are actively growing and soil moisture is adequate. Using modest doses of fertiliser at suitably spaced intervals helps avoid losses via leaching, volatilisation and denitrification.

The efficiency of nitrogen use by feed crops can be further enhanced by the judicious use of nitrification inhibitors – chemical compounds added to fertilisers or soil to slow down the biological conversion of ammonium into nitrate. As well as improving crop nitrogen use efficiency, nitrification inhibitors reduce nitrate leaching and lower nitrous oxide emissions (Abalos et al. 2014).

[11] https://www.atlasagro.ag/nitrate-staging/

AGRONOMY AND SOIL ORGANIC CARBON SEQUESTRATION

Agronomy can lower GHG emissions from dairy feed production mainly by improving crop nitrogen use efficiency, maintaining productive soils and avoiding practices that waste carbon and nitrogen. The biggest benefits usually come from cutting nitrous oxide losses, reducing the need for fertiliser inputs, increasing soil organic carbon and lowering the EI of home-grown feed.

Cover crops capture residual soil nitrogen after harvest, reducing nitrate loss and the risk of subsequent N_2O emissions, while also improving soil cover and erosion control (Abdalla et al. 2019). Legume-based cover crops can also reduce the need for N fertiliser in the following crop, cutting both direct field emissions and upstream fertiliser manufacturing emissions. Cover crops also help build soil organic matter over time, which supports feed productivity and improves the GHG intensity of forage production. Meta-analyses and regional studies report that winter cover crops can reduce N_2O and fertiliser-related emissions, with net mitigation potentials around 1.9 t CO_2 eq. per ha per yr (Eagle et al. 2012).

Maintaining soil pH in the optimum range of around 6.5 for arable land and about 6.0 for grassland improves nutrient availability and crop uptake, which raises forage yield and reduces emissions per tonne of feed produced (Wang et al. 2017). Liming acid soils can also reduce N_2O emissions. Hénault et al. (2019) estimated that liming could potentially decrease France's total N_2O emissions by 15.7%, based on an estimate that 37% of fertilised soils in France are acidic.

Restoring degraded cropland improves soil structure, organic matter, water retention and erosion resistance, which can increase and stabilise fodder yields while rebuilding soil carbon. In GHG terms, restoration reduces CO_2 losses from disturbed or depleted soils and can shift land towards a net sink rather than a source, especially where degraded land is converted to permanent grassland or other restorative cover.

This is particularly relevant for dairy feed systems because more productive, resilient land reduces the EI of home-grown feed and lessens pressure to expand production onto lower-quality land.

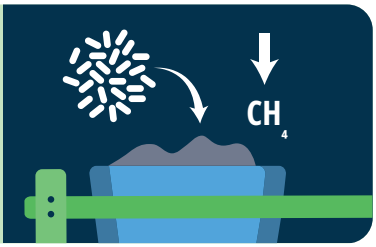
Biochar can be applied to soils growing forage to increase soil carbon storage, improve nutrient and water retention, and sometimes lift fodder yield and quality (Singh et al. 2022). Logistical and economic hurdles to its adoption, however, will need to be addressed before its use becomes more widespread.

Stopping residue burning avoids immediate emissions of CO_2, CH_4, N_2O and black carbon, and it prevents the loss of organic matter that could otherwise be returned to the soil. Retaining, incorporating or otherwise recycling residues helps build soil carbon and fertility, improves moisture conservation, and reduces the need for fertiliser inputs. FAO climate-smart agriculture guidance explicitly treats ending residue burning as a core mitigation practice alongside cover crops and improved soil management (FAO 2013b).

USE OF BY-PRODUCTS

The use of agro-industry by-products, such as distillers' grains, brewers' grains, beet pulp, wheat middlings and oilseed meals, and the waste from fruit processing for human consumption, makes use of valuable sources of fibre, energy and protein whose emissions are shared between their primary purpose and their secondary use as dairy feed. Several studies have found the inclusion of by-products in diets to lower feed-related GHG emissions, while maintaining performance (e.g. Lindberg et al. 2021; Managos et al. 2025). The climate benefit of using by-products depends on what the by-product displaces, how far it is transported and whether it fits the ration nutritionally without hurting production (de Ondarza and Tricarico 2021).

5. METHANE-SUPPRESSING FEED SUPPLEMENTS



Methane-reducing technologies can substantially reduce emissions, but the best results come when they are combined with improvements in productivity, manure handling and overall herd efficiency rather than used in isolation (de Ondarza et al. 2023). Reviews indicate that several compounds can reduce methane production in the rumen of dairy cattle (e.g. Cottle et al. 2011; Dalmonte et al. 2026). Nitrate added to the diet, for example, can reduce methane by competing with methanogenesis for hydrogen in the rumen. Certain lipids, especially medium-chain fatty acids and polyunsaturated fatty acids, also reduce methane by limiting the availability of hydrogen. Some plant secondary compounds, including tannins and saponins, as well as some essential oils, have been found to act as methane inhibitors. Monensin and other ionophores may give a modest reduction in some situations. However, the biggest reported effects in dairy cows are for 3-NOP and, among natural products, seaweeds of the genus *Asparagopsis.*

3-NITROOXYPROPANOL (3-NOP)

A promising methane-suppressing feed supplement is 3-nitrooxypropanol (3-NOP). 3-NOP consistently reduces enteric methane by 25-33% in published in vivo studies and has shown no major penalty to milk yield in several trials; some long-term work even reports higher energy-corrected milk and better feed efficiency (Kebreab et al. 2023). 3-NOP works by binding to a specific enzyme in methanogenic Archaea in the rumen, thereby disrupting methane production. 3-NOP is marketed under the brand name Bovaer® and has been approved for use in more than 68 countries and the EU, including Great Britain, Australia, Canada, and the US.[12] The response depends on diet, dose, timing and duration. One study showed that 3-NOP fed to calves conferred methane-reducing effects that persisted later in life (Meale et al. 2021).

[12] https://www.dsm-firmenich.com/anh/products-and-services/products/methane-inhibitors/bovaer.html

ASPARAGOPSIS SEAWEEDS

The red seaweed species *Asparagopsis taxiformis* and *A. armata* can also suppress rumen methane production when fed as a supplement to dairy animals. *Asparagopsis* species contain high levels of bromoform, a halogenated methane analogue that interferes with the final step of methanogenesis in the rumen, effectively blocking the conversion of hydrogen and carbon dioxide into methane (Bačėninaitė et al. 2022). Studies report methane reductions ranging widely, from 9% to 70%, depending on seaweed type, dose and trial duration, though effects can diminish over time due to microbial adaptation (Kebreab et al. 2025). However, seaweed still faces some challenges to its widespread adoption as a mainstream methane-reducing feed additive. Residues of iodine, bromine and bromoform in milk or meat, as well as the complexities of establishing a supply chain for seaweed cultivation, preservation and processing, have hampered progress (Liu et al. 2025). While the methane-suppressing efficacy of *Asparagopsis* is indisputable, its application as a commercial feed supplement must overcome several hurdles related to supply chains, consumer acceptance, safety, costs, logistics, policy incentives and regulations.

While bromoform can be manufactured synthetically, research shows that whole seaweed of the genus *Asparagopsis* works significantly better than synthetic bromoform alone for reducing livestock methane emissions (Ahmed and Nishida 2024).

With all methane-suppressing feed supplements, there is a need to address the economics of their use as, in general, they do not deliver additional milk yield. For their use to be economically viable, there therefore needs to be some form of financial incentive linked to the reduction of methane emissions. Beyond technical efficacy, widespread adoption of methane-suppressing feed supplements will depend on their cost-effectiveness, regulatory approval, farmer acceptance and confidence among consumers.

THE INTERACTION BETWEEN LEVERS AND DAIRY SYSTEMS

It has been stated that these different nutritional levers vary in their importance and relevance, and indeed in their implementation, across the different dairy systems described earlier (Figure 1). In this section, the relevance of the different levers, and the specific measures under them, has been linked to each of the dairy systems. This was achieved by looking at studies that estimated the GHG abatement potential of different measures in dairy systems. The studies are based on analyses using marginal abatement cost curves (MACC), an analytical tool used to compare and rank different carbon-reduction actions by their financial cost and their potential volume of emissions reduced. The studies incorporated are from a range of countries as follows: UK (IGD 2024); Ireland (Teagasc 2023); France (Pellerin et al. 2013); USA (Jones and O'Hara 2023); India (Sapkota et al. 2019); and Costa Rica (Duffy et al. 2021).

The following table (table 1) illustrates the variation in relevance of the different measures among the systems. For example, all measures are relevant to some degree in the more advanced dairy systems, but some measures are not pertinent to the less developed systems. Moreover, a measure in one type of system may look rather different from the same measure in another.

On a smallholder dual-purpose farm, for example, ration formulation may involve some quite basic diet formulation with a view to achieving sufficiency, including ensuring adequate water provision. The same measure in a high-input, high-output farm would likely involve highly sophisticated precision feeding and monitoring.

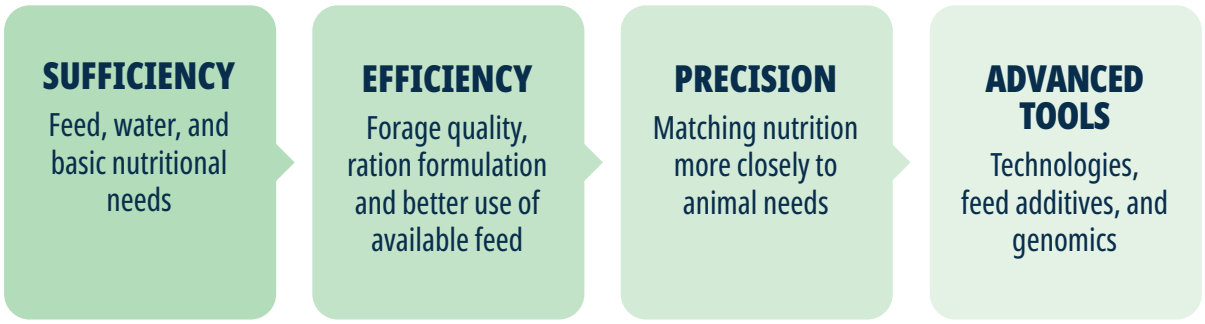
TABLE 1. Estimated abatement potential by measure and system. The values in the cells refer to the abatement potential for greenhouse gases, with 'l' referring to minimal abatement potential, 'm' to medium potential and 'h' to considerable potential for abatement in those systems. These are indicative assessments drawn from different studies and should not be interpreted as directly comparable, quantified estimates of emissions reductions.

Lever	Category	Pastoral and agropastoral	Smallholder, dual-purpose	Smallholder, specialised	Pasture-fed	Medium scale, specialised	High-input, high-output
1. Improved feeding practices	Sufficiency	h	h	m	l	l	l
	Prep. and presentation	l	h	h	m	h	m
	Optimised feeding throughout the animal's life	m	h	h	h	h	h
	Ration formulation	h	h	h	h	h	h
	Improving feed materials	h	h	h	m	h	m
2. Forage and pasture management	Optimising grazing	m	h	h	h	h	h
	Forage conservation	l	m	m	m	h	h
	Avoiding LUC	l	l	l	h	h	h
	Low-carbon fertiliser	l	m	m	m	m	m
	Improved nitrogen use efficiency by pasture	m	h	h	h	h	h
	Agronomy and C sequestration	h	h	h	h	h	h
3. Livestock management	Herd management	m	m	m	m	m	h
	Breeding for feed efficiency	h	h	h	h	h	h
	Cattle health and welfare	h	h	h	h	h	h
4. Lower-emissions feed	Avoiding LUC	l	m	m	h	h	h
	Low-carbon fertiliser	l	m	m	m	m	m
	Improved nitrogen use efficiency by crops	l	h	h	m	h	h
	Agronomy and C sequestration	l	h	h	h	h	h
	Use of by-products	l	m	m	m	m	m
5. Methane-suppressing feed supplements	3-nitrooxypropanol (3-NOP)	l	m	m	m	h	h
	Asparagopsis seaweeds	l	m	m	m	h	h

INTEGRATED APPROACH

It is apparent from the previous sections that there are multiple interactions among these five levers to optimise nutrition. Depending on the dairy system, these levers should be implemented to appropriate degrees and integrated in combinations that suit the prevailing conditions and system objectives. Following a pathway towards better productivity and lower GHG emissions also requires an appropriate sequencing of interventions. There is little advantage to be had from introducing advanced interventions if a generally positive nutritional status is not already in place. Figure 3 provides a schematic of how different types of intervention might be sequenced: building from the left, before investing in the right.

FIGURE 3. Schematic showing how different types of intervention might be sequenced – starting with those on the left and moving towards the right as the system develops.



To have maximum impact on yield improvements and GHG reductions, optimising nutrition needs to be considered within a broader package of interventions including health, welfare, genetics, herd management and husbandry.

A meta-analysis of dairy management strategies in East Africa, for example, showed that improved feeding – when combined with improved breeding – accounted for at least half of the improvement in daily milk yield achieved on-farm. This underscores the importance of aligning ration quality with genetic potential (Bateki et al. 2020). The same applies in more advanced dairy systems. Scenario modelling suggests that combining improved feeding with reproductive and health management on an average Scottish dairy farm produces the largest reductions in EI (Ferguson et al. 2024).

CO-BENEFITS AND SUSTAINABILITY CONSIDERATIONS

The focus of this paper is to promote optimal nutrition of dairy herds to maximise yields and profit and minimise GHG emissions. Optimising nutrition, however, has several co-benefits across other important domains of sustainability. These can be organised along four dimensions of sustainability defined by the Global Forum for Food and Agriculture in 2018 (FAO 2018): food and nutrition security, livelihoods and economic growth, animal health and welfare, and climate and natural resource use.

FOOD AND NUTRITION SECURITY

For most producers, optimising nutrition for dairy animals involves maximising profits and ensuring a reliable, affordable supply of clean, high-quality milk and dairy products. This should in turn enhance the important role dairy already plays in food and nutrition security.

Milk and dairy foods provide variety to the diet and make significant contributions to meeting the needs for high-quality protein, calcium, magnesium, selenium, riboflavin, vitamin B12, and vitamin B5 (Otte et al. 2012).

This high-quality nutrient package is difficult to replace without dairy or other animal-sourced foods, particularly for vulnerable groups such as children, pregnant women and the elderly.

Whether from subsistence systems, where milk may well be the main source of nutrition, or from more developed systems that supply milk to markets where it is processed into a diverse range of products for human consumption, milk plays a fundamental role in food and nutrition security.

LIVELIHOODS AND ECONOMIC GROWTH

With generating or increasing profits as a primary objective for most dairy systems, nutrition optimisation links directly to improved livelihoods and economic growth. It is, however, important to ensure that opportunities to intensify dairy production in this way are equitable. This is particularly so in emerging economies, where gains in productivity need to be paired with rules and support that spread benefits fairly and prevent new burdens from falling on already disadvantaged farmers, workers, and household members. The strongest approaches combine technical improvement with social safeguards, market access and participation in decision-making (Clay et al. 2020).

Dairy cow ownership has been associated with significant increases in household income (27-115%) and improved diet quality across multiple countries, including, for example, Bangladesh, Ethiopia, Kenya, India and Tanzania (Tricarico et al. 2020). However, livestock in these settings serve multiple non-food roles, including draft power, manure for fuel and fertiliser, savings, insurance, cultural and dowry functions. In these cases, the diverse

objectives of dairy systems may incentivise maintaining large herds of low-producing animals and place strain on feed and water resources.

For low-income countries, the sustainable intensification of dairy systems – increasing milk production from existing resources without converting additional land – is identified as the single most important strategy to improve the sustainability of milk production and consumption.

Key approaches include improving the quality and availability of feed and water, balancing animal nutrition and improving genetic potential (Tricarico et al. 2020). Technologies from high-income countries cannot be adopted directly but must be adapted to local conditions, resources, and climatic circumstances and, importantly, be both accessible and affordable.

ANIMAL HEALTH AND WELFARE

There are good examples of animal health and welfare benefits that result from optimising the nutritional status of dairy cows. Precision feeding and the use of higher-quality, more digestible rations can support rumen function by helping maintain stable ruminal pH and fibre digestion, thereby reducing the risk of ruminal acidosis and associated digestive and metabolic disturbances (González et al. 2018). This can keep veterinary costs down and reduce replacement pressure within herds. Well-balanced diets improve immune function, metabolic stability and fertility, reducing the incidence of disease and supporting longer productive lifespans.[13]

But the relationship between animal health and welfare and animal nutrition goes both ways: as several earlier examples show, good health is a prerequisite for the benefits of optimised nutrition to be realised.

We must not compromise the animals' ability to perform by managing them poorly and placing them in environments that inhibit the expression of their genetic potential. These critical aspects of dairy production must be aligned.

CLIMATE AND NATURAL RESOURCE USE

While the climate benefits of optimised nutrition are well established, there are also environmental co-benefits in terms of avoiding excess nutrient loading in animal waste. Optimal nutrition reduces excess nitrogen and organic matter excreted, lowering nitrous oxide and manure-related emissions as well as nutrient losses.[14] By raising output per cow and per hectare, optimised feeding can contribute to land sparing, with less area needed for the same amount of milk produced, supporting broader mitigation and biodiversity objectives when combined with appropriate land use planning (Hawkins et al. 2021).

[13] https://ahdb.org.uk/whole-farm-feed-efficiency-wffe
[14] https://ahdb.org.uk/whole-farm-feed-efficiency-wffe

SCALING UP THE IMPACTS – TWO CASE STUDIES

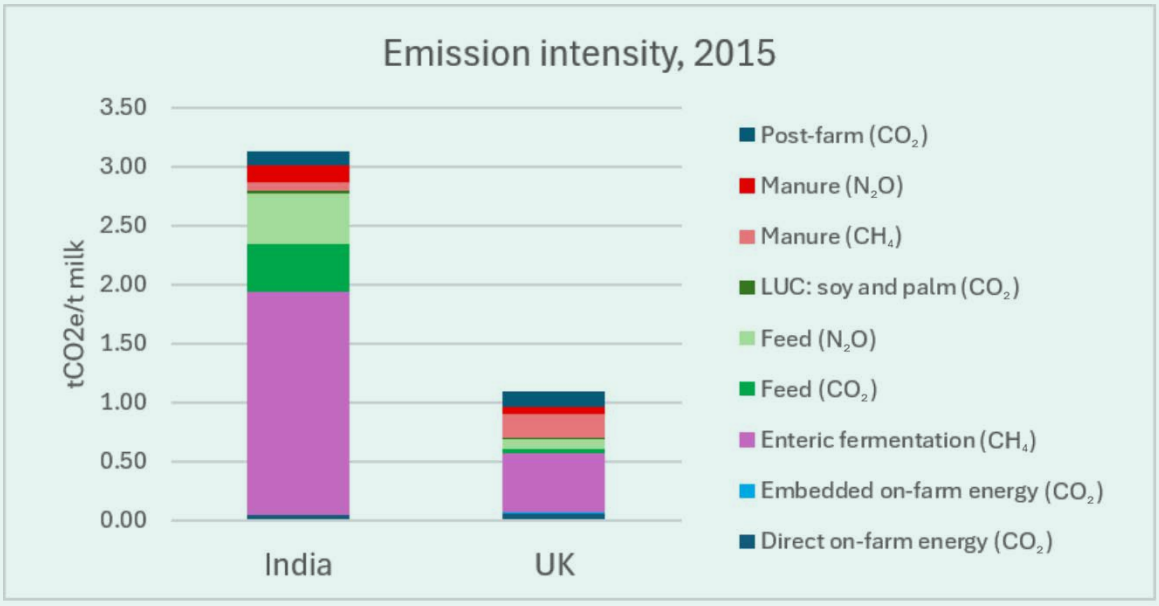
This section of the paper builds on previous discussions to assess the potential impact of feed interventions on GHG EIs in two contrasting example countries: India and the UK.

This assessment draws upon a comprehensive analysis undertaken to substantiate this paper. The analysis quantifies future trends in bovine milk GHG emissions to 2050 using a four-step method:

1. Source data on trends in milk production and milk yields and estimate them in 2050.
2. Estimate EI to 2050 based on the relationship between milk yield and EI illustrated in Figure 1.
3. For each country, identify three relevant feed-related mitigation measures from Table 1 that can be used to further reduce GHG emissions and estimate their effect on EIs.
4. Calculate emissions to 2050 for three cases: 1) milk yield and EI remain constant; 2) milk yields increase and EI decreases, following the relationship shown in Figure 1; and 3) Case 2, with the additional implementation of three mitigation measures for each country.

The contributions of different GHG sources to the EI of bovine milk production in India and the UK were examined to identify suitable mitigation measures. Figure 4 shows EI in India to be three times that of the UK and that most of the emissions arise from feed production and enteric fermentation, positioning these sources as targets for mitigation measures. Enteric fermentation accounts for about 61% of emissions in India, compared to about 45% in the UK.

FIGURE 4. Emissions intensity of bovine milk production in India and the UK, 2015 (based on GLEAM 3 data, FAO 2022)



Based on a review of the literature, interventions were selected for the UK and India, drawing from different levers. These measures are described in Table 2.

The abatement potential of each measure was modelled using three parameters: i) the rate of farmer uptake, ii) the proportion of the relevant GHG source targeted, and iii) the per-unit reduction achieved. Table 3 summarises the key assumptions and estimated maximum abatement by 2050. The abatement percentages are simple products of uptake × targeting × per-unit reduction. These estimates indicate the maximum effect on the targeted GHG pool under modelled adoption rates, not necessarily whole-system abatement.

TABLE 2 . Summary of the mitigation measures modelled. "Lever" and "Category" refer to the typology in Table 1.

Country	Measure	GHG targeted	Description	Lever	Category
India	Improved fertiliser use	Feed crop N_2O and CO_2	Improving the efficiency of nitrogen use during feed crop production by optimising the amount, timing, type of N etc. (Sapkota et al. 2019)	4. Lower-emissions feed	Improved nitrogen use efficiency by crops
India	Feed additives	Enteric CH_4	Use of tannin-based additive (e.g. 'Harit Dhara', Kona et al. 2025), 'molasses urea product' (Sapkota et al. 2019)	5. Methane-suppressing feed supplements	Other
India	Increasing concentrates	Enteric CH_4	Increasing the amount of concentrate feed in the ration (Sapkota et al. 2019)	1. Improved feeding practices	Ration formulation
UK	Grass-legume mixes	Feed crop N_2O and CO_2	Increasing the legume-grass mix areas and increasing the proportion of clover in the mixed swards	2. Forage and pasture management	Improved nitrogen use efficiency by pasture
UK	Feed additives	Enteric CH_4	Use of 3-NOP (e.g. Martins et al. 2025)	5. Methane-suppressing feed supplements	3-NOP
UK	Precision feeding	Enteric CH_4 Feed crop N_2O and CO_2 Manure N_2O and CO_2	Tailored feed supplementation based on frequent analysis of feed quality, particularly forage, and daily recording of milk yield and cow weight with automated weighing system	1. Improved feeding practices	Ration formulation

TABLE 3. Key abatement assumptions and estimated maximum mitigation potential by 2050. Abatement estimates are illustrative and depend on actual adoption rates. The data and assumptions are drawn from a variety of sources, described in detail in the analysis report.

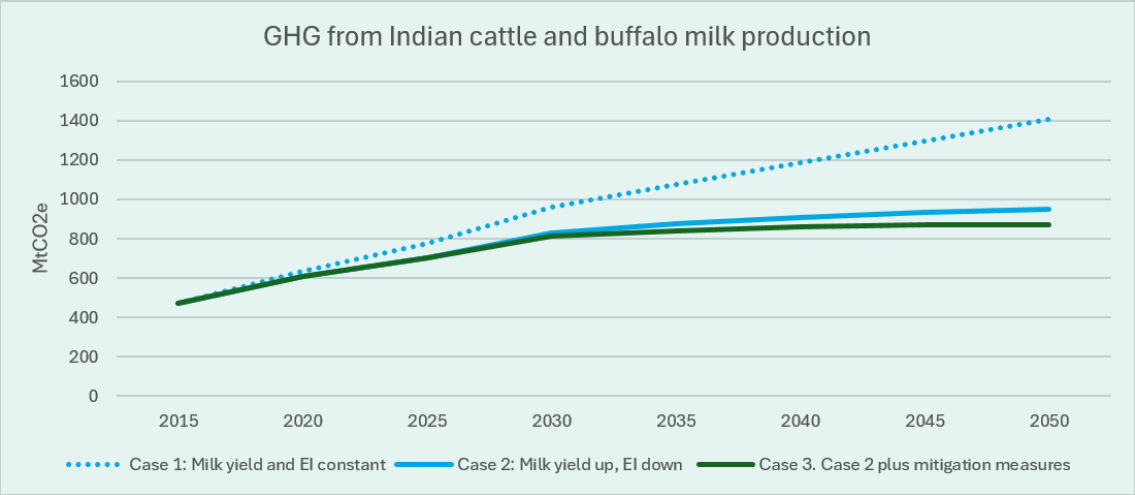
Country	Measure	GHG targeted	Additional uptake by 2050	% of GHG targeted	Reduction of targeted GHG	Estimated maximum abatement of targeted GHG	Estimated maximum abatement of total GHG
India	Improved fertiliser use	Feed crop N_2O and CO_2	70%	70% of feed N_2O and CO_2	30%	14.7%	3.9%
India	Feed additives	Enteric CH_4	40%	60% of enteric CH_4	20%	4.8%	2.9%
India	Increasing concentrates	Enteric CH_4	30%	60% of enteric CH_4	15%	2.7%	1.6%
UK	Grass-legume mixes	Feed crop N_2O and CO_2	50%	70% of feed N_2O and CO_2 (via N reduction)	50%	17.5%	1.9%
UK	Feed additives	Enteric CH_4	90%	80% of herd (50% of time)	20%	7.2%	3.3%
UK	Precision feeding	Enteric CH_4; feed and manure N_2O and CO_2	50%	80% of herd (50% of time)	4%	0.8%	0.7%

INDIA: PROJECTED EMISSIONS TO 2050

India's dairy sector is the world's largest and is growing rapidly. The extent to which this growth translates into rising emissions depends critically on whether productivity gains continue and whether targeted mitigation measures are adopted. Under the constant-yield Case 1, emissions could nearly double from ~775 Mt CO_2 eq. in 2025 to ~1,400 Mt CO_2 eq. by 2050. Yield-driven EI reductions (Case 2) could constrain this to ~950 Mt CO_2 eq., while the addition of the three modelled mitigation measures (Case 3) could further reduce 2050 emissions to ~870 Mt CO_2 eq.

The key finding for India is that improvements in productivity and the deployment of mitigation measures could substantially limit the increase in emissions relative to the constant-yield scenario, but significant reductions below 2025 emissions appear challenging given the forecast growth in India's dairy sector.

FIGURE 5. Estimated total emissions from bovine milk production in India

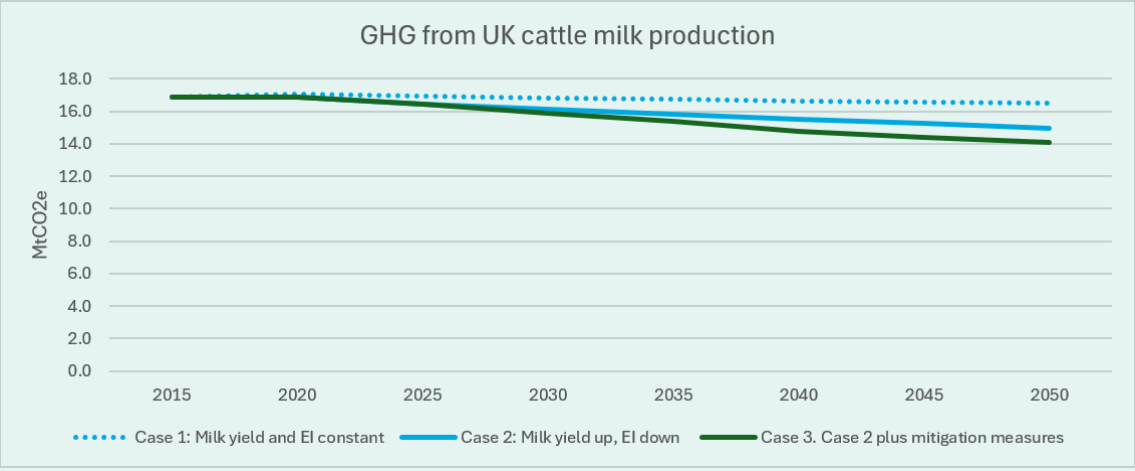


UK: PROJECTED EMISSIONS TO 2050

The UK dairy herd has undergone significant structural change in recent years. Milk yield per cow has increased, and sexed semen has been rapidly adopted, increasing the availability of replacement heifers and dairy-bred beef calves while enabling more targeted genetic improvement (AHDB 2026).

While the EI of UK milk is already low by international standards, further reductions are achievable. Under the constant-yield Case 1, emissions remain very similar to their 2025 level of ~16.5 Mt CO_2 eq., decreasing only very slightly. Yield-driven EI reductions (Case 2) could reduce this to ~15 Mt CO_2 eq., while the addition of grass-legume mixes, 3-NOP feed additives and precision feeding (Case 3) could further reduce emissions to ~14 Mt CO_2 eq.

FIGURE 6. Estimated total emissions from cattle milk production in the UK



CASE STUDY CONCLUSIONS

Feeding-based interventions represent a significant opportunity to reduce GHG emissions from dairy production in both India and the UK, though the scale of the challenge differs markedly between the two systems.

India's dairy sector is expanding rapidly, with milk production projected to reach 450 Mt by 2050 (OECD-FAO 2026; Kona et al. 2025). Without productivity improvements, this growth could push emissions from approximately 500 Mt CO_2 eq. in 2015 to nearly 1,400 Mt CO_2 eq. by 2050. However, yield-driven reductions in EI combined with three targeted mitigation measures could constrain 2050 emissions to around 870 Mt CO_2 eq., a reduction of about 40% relative to the constant-yield case, though still 12% above the 2025 level (~775 Mt CO_2 eq.).

The UK dairy sector, with already-low EI (~1.1 t CO_2 eq. per tonne of milk versus ~3.1 in India), faces a different challenge. Continued improvements in productivity, fertility, and genetics are projected to reduce emissions from approximately 16.5 Mt CO_2 eq. in 2025 to around 15 Mt CO_2 eq. by 2050. The addition of grass-legume mixes, 3-NOP feed additives, and precision feeding could further reduce emissions to approximately 14 Mt CO_2 eq., a reduction of roughly 15% from the constant-yield baseline. Applying these approaches as mitigation for the UK sector is not a one-off reduction but a change in practice to maintain those reductions and sustain them in times of volatility.

The relative importance of the mitigation measures differs between the two systems. In India, improved fertiliser use offers the largest modelled abatement (14.7% of targeted emissions), reflecting the very low baseline nitrogen use efficiency of crops in India (about 30%) (Sapkota et al. 2019). In the UK, grass-legume mixes provide significant abatement potential (17.5% of targeted emissions), driven by the ability to halve synthetic nitrogen application through biological fixation. This assumes, however, that the same level of productivity is maintained on the mixed sward. Enteric methane inhibitors (tannin-based additives in India and 3-NOP in the UK) offer significant abatement in both systems. Further emissions reductions can be achieved via feeding more concentrates in India and adopting precision feeding in the UK.

The abatement from the mitigation measures is illustrative. In practice it may be possible to increase the abatement via increased uptake or the adoption of other measures, such as restoring degraded cropland in India (Sapkota et al. 2019), carbon sequestration (e.g. via agroforestry, biochar or enhanced weathering) or lower-carbon alternative feeds such as single-cell protein (CIEL 2023).

In both systems, the yield-driven reduction in EI (Case 2) accounts for most of the total emissions reduction relative to the constant-yield baseline. This underscores the importance not only of nutrition but also of health, breeding, husbandry and fertility improvements as foundational mitigation strategies. Feeding-based interventions contribute an additional layer of abatement on top of these productivity gains.

WHAT CAN BE DONE

The arguments presented here make a compelling case for optimising nutrition as a practical opportunity to improve productivity and profitability while reducing GHG emissions in dairy systems. The evidence demonstrates that better nutrition can deliver multiple benefits simultaneously. Yet, despite this potential, nutritional practices are not always optimised across dairy systems.

Unlocking this opportunity will require a clear understanding of the specific factors that influence nutritional decision-making in each dairy system. These may include technical, economic, knowledge, infrastructure and market considerations, as well as the incentives available to farmers and other value-chain actors. These factors will vary considerably between systems and regions. Identifying and addressing them will be critical to putting optimised nutrition at the heart of sustainable dairy development and enabling farmers to capture its productivity, profitability and environmental benefits.

Achieving this ambition will require collaboration across the dairy value chain. Policy makers, researchers, veterinarians, dairy nutritionists, farmers, feed companies and other industry actors all have important roles to play in creating the conditions for improved nutrition and supporting its adoption at scale.

A central lesson from this analysis is that improving animal nutrition offers one of the clearest opportunities to align the economic interests of dairy farmers with environmental outcomes. Particularly in lower-productivity systems, better feeding can improve farm profitability while reducing emissions per unit of milk. This creates a strong foundation for sustainable dairy development, upon which more advanced mitigation technologies can be introduced as they become technically and economically viable.

A range of complementary actions can help unlock this potential. These could include:

- Supporting forage improvement and access to higher-quality feed resources.
- Accelerating access to precision feeding technologies that enable farmers to better match diets to animal requirements.
- Strengthening advisory, extension and knowledge-transfer systems so that practical nutritional expertise reaches farmers.
- Strengthening the relationship between dairy farmers and feed advisors to optimise nutrition and nutrition management for maximum impact on farm productivity and GHG mitigation.
- Creating incentives for carbon sequestration in pastures, recognising the wider environmental benefits that well-managed grazing systems can provide.

- Streamlining the approval and adoption of safe, effective feed additives with demonstrated nutritional and environmental benefits.
- Encouraging the effective recycling of energy and nutrients from manure, contributing to more circular and resource-efficient dairy systems.
- Supporting breeding and selection for improved feed efficiency and lower emissions, alongside other desirable animal health and productivity traits.
- Strengthening measurement, reporting and verification systems to demonstrate progress, build confidence and support informed decision-making.

Together, these actions can help move optimised nutrition from being an underused opportunity to a central component of productive, profitable and lower-emission dairy systems. The opportunity is not simply to produce more efficiently, but to create a virtuous cycle in which better nutrition supports healthier animals, stronger farm businesses, more efficient use of resources and improved environmental outcomes.

REFERENCES

For the full list of references, please visit:
https://globaldairyplatform.com/references-more-milk-better-margins-lower-emissions





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