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## Sustainable and regenerative cattle production systems: Literature review

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**Abstract.** Cattle production remains relevant to global food systems due to its links with food security, environmental impacts, animal welfare, and societal expectations. The purpose of this review was to examine the role of beef and dairy cattle within sustainable and regenerative agricultural systems using an integrated, systems-based perspective. The review was based on a critical synthesis of peer-reviewed literature addressing environmental performance, methane emissions, animal welfare, regenerative management practices, and socio-economic dimensions of cattle production. Sustainability frameworks used in cattle systems were analysed, with particular attention to the limitations of single-metric assessments such as greenhouse gas emissions. The biological basis of methane production and its relationship with feed efficiency, animal health, and management was described. Evidence on regenerative beef and dairy practices, including grazing management, soil carbon dynamics, biodiversity outcomes, and nutrient cycling, was examined. The role of animal welfare was analysed through One Health, One Welfare, and One Biology frameworks, highlighting its integration with productivity, emissions intensity, and system resilience. Gaps in current sustainability assessments and research methodologies were identified, particularly regarding long-term system performance, welfare indicators, and policy coherence. The findings of this review can be used by researchers, policymakers, advisors, and farmers to support the design, assessment, and implementation of cattle systems that align productivity with environmental stewardship and animal welfare

**Keywords:** agroecosystems; animal welfare; greenhouse gas emissions; methane mitigation; one health; one welfare; regenerative agriculture

### INTRODUCTION

Cattle production (beef and dairy) remains a cornerstone of global agricultural systems, providing milk, meat, and ecosystem services while supporting the livelihoods of hundreds of millions of people worldwide. S.E. Place (2024) emphasised that ruminant

livestock, including cattle, possess a digestive physiology that enables them to convert fibrous and otherwise non-human-edible forage into nutrient-dense meat and milk, and concluded that this capacity allows cattle to contribute uniquely to sustainable food systems by

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producing high-quality human nutrition from marginal resources. A. Domínguez-Hernández *et al.* (2025) further showed that cattle have historically stimulated mixed crop-livestock systems by recycling nutrients through manure and converting forages and crop residues into food, forming the agronomic basis of both traditional systems such as the Norfolk rotation and modern integrated and regenerative farming approaches.

Sustainability in cattle systems is inherently multidimensional, encompassing environmental integrity, animal welfare, economic viability, and social acceptability. N. Britten & S. Mahendran (2025) emphasised that sustainability assessments have historically prioritised environmental indicators such as land use, water consumption, and greenhouse gas (GHG) emissions, often neglecting animal welfare and biological functioning. S.J. Hendriks *et al.* (2025) argued that welfare should be integrated as a core sustainability component rather than treated as an ethical add-on. Among environmental concerns, GHG emissions from cattle have received particular attention. S. Malyugina *et al.* (2025) quantified enteric methane emissions as a significant component of global agricultural methane output and identified enteric fermentation as the dominant source. J.V.A. Muller (2025) noted that this has driven climate policy and research to focus strongly on methane mitigation strategies.

Cattle systems vary widely in structure and impact, ranging from intensive feed-based systems to extensive grazing systems embedded within complex landscapes. R. Teague & U. Kreuter (2020) demonstrated that well-managed grazing systems can enhance soil carbon storage, nutrient cycling, and habitat provision, particularly when aligned with regenerative or agro-ecological principles. In contrast, X. Niu *et al.* (2025) showed that poorly managed systems, regardless of intensity, can contribute to land degradation, biodiversity loss, and compromised animal welfare. These findings highlighted the need for sustainability assessments that evaluate management quality and context rather than generic comparisons of cattle versus alternative food systems. Animal welfare represents a critical but often underrepresented pillar of sustainable cattle production. L. Boyle & P. Stevenson (2025) reported that poor health, chronic stress, and suboptimal living conditions reduce productivity and increase resource use per unit of output. Methane emissions must therefore be interpreted within a broader biological and management context. B.-R. Min *et al.* (2022) showed that enteric methane represents an energetic loss of 2-12% of gross energy intake and concluded that strategies improving feed efficiency and rumen function can reduce emissions per unit of product. H.R. Albarki *et al.* (2025) provided evidence that nutritional interventions, genetic selection for feed efficiency, and improved pasture quality can simultaneously enhance productivity, welfare, and emissions performance. These authors

highlighted that such approaches align with regenerative principles by optimising biological function rather than targeting methane reduction in isolation. Regenerative cattle farming has emerged as a proposed pathway to reconcile production with ecological restoration.

N. Adams *et al.* (2025) highlighted policy pressures to reduce agricultural emissions alongside rural development goals. Sustainability strategies must balance environmental performance, ethical considerations, and farmer livelihoods to maintain social legitimacy. These findings reinforced the need for integrative frameworks that recognise cattle as biological agents within complex agroecosystems rather than solely as sources of environmental burden. This review aimed to clarify how cattle production systems can contribute to sustainability and regeneration when evaluated through integrated environmental, animal welfare, and socio-economic perspectives. Specifically, the objectives were to: (i) examine how management-driven improvements in biological efficiency and animal welfare influence environmental performance, including emissions intensity; (ii) assess the potential and limitations of regenerative beef and dairy systems across different production contexts; and (iii) identify key gaps in current sustainability frameworks that arise from reliance on single metrics, particularly methane emissions.

A narrative review approach was employed to synthesise current knowledge on sustainable and regenerative cattle systems. Peer-reviewed literature published primarily between 2019 and 2025 was identified using targeted searches in the major scientific databases (Web of Science, and Scopus) with keywords related to cattle production, sustainability, methane mitigation, animal welfare, and regenerative agriculture. Sources were selected based on relevance, methodological robustness, and applicability to beef and dairy systems, and were analysed thematically to integrate findings across environmental, biological, and socio-economic dimensions.

### ANIMAL WELFARE AND ONE HEALTH

Animal welfare has emerged as a critical component of sustainability assessments in livestock production, particularly for cattle, as societal expectations increasingly demand that welfare outcomes be considered alongside environmental and economic performance. L. Boyle & P. Stevenson (2025) emphasised that societal pressure is driving the integration of welfare considerations into sustainability frameworks, while Q. Zhang *et al.* (2023) highlighted that ignoring welfare may undermine the perceived legitimacy of livestock systems. Traditional sustainability frameworks often focus on measurable metrics such as GHG emissions or land use, but this narrow focus can overlook welfare dimensions that are inherently biological, behavioural and affective in nature. Contemporary animal welfare science emphasised that welfare is not simply the absence of disease or stress

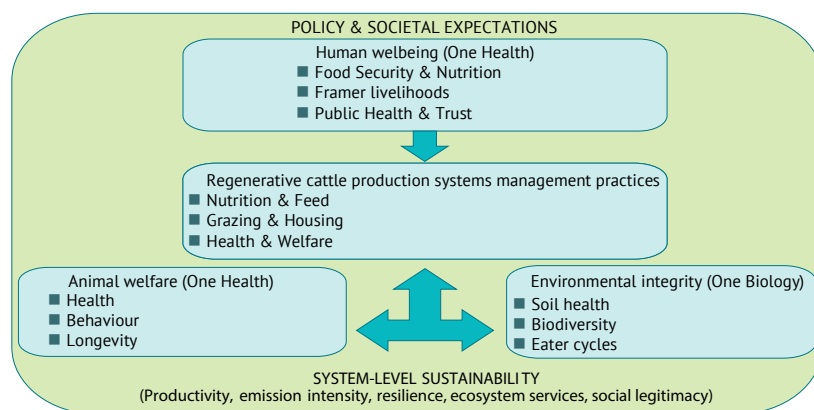
but also includes the animal's ability to express natural behaviours, maintain good health, and achieve a positive mental state, elements captured in established conceptual models such as the Five Domains framework. The One Health paradigm, endorsed by global health authorities, recognises the interdependence of human, animal and ecosystem health, and it has become foundational in understanding complex agro-ecosystem challenges. S.J. Pitt & A. Gunn (2024) argued that One Health promotes interdisciplinary collaboration to address shared threats such as zoonoses, antimicrobial resistance, and food safety, yet they note that broader welfare outcomes are often underemphasised.

However, One Health traditionally emphasises disease and health outcomes more than broader welfare concerns. This has led to the development of One Welfare, an extension of One Health that explicitly integrates animal welfare with human well-being and environmental sustainability within a single comprehensive framework. S. Platto *et al.* (2025) argued that One Welfare recognises the bidirectional relationship between animal and human welfare and their joint dependency on environmental integrity. The relevance of One Welfare to livestock systems is notable: production animals such as cattle not only influence but are influenced by the health and well-being of their caretakers, consumers and the ecosystems they live in. C. Spigarelli *et al.* (2021) demonstrated that improvements in animal welfare can enhance farmer satisfaction and ecosystem services, suggesting practical benefits beyond ethical considerations. In the context of regenerative agriculture, systematic analysis illustrated that current research often links animal welfare outcomes to animal health and human financial or psychological well-being, and environmental conservation. M.J. Hargreaves-Méndez & M.J. Hötzel (2023) concluded that welfare actions are integral to broader sustainability goals, reinforcing the need to move beyond narrow environmental or economic metrics. Despite the conceptual advances, operationalising One Welfare within cattle production systems remains challenging, as welfare assessments are

variably integrated into sustainability models. A. van der Linden *et al.* (2020) observed that many decision-support tools still inadequately capture welfare alongside environmental and socio-economic indicators, limiting their utility for holistic system management.

The literature argued that embedding welfare into sustainability requires systems-level thinking and interdisciplinary collaboration across veterinary science, animal behaviour, ecology, public health and policy domains. C. Ducrot *et al.* (2024) emphasised that integrating welfare indicators with societal outcomes, such as public trust, is essential for resilient and socially acceptable livestock systems. In practical terms, welfare improvements can enhance production efficiency and reduce disease burdens. J.K. Lane *et al.* (2025) found that interventions such as improved housing and nutrition reduced infectious disease incidence, thereby decreasing antimicrobial use and associated costs, aligning with One Health goals. Although much of the One Welfare literature remained emergent S. Platto *et al.* (2025) pointed out that welfare must be central to sustainability evaluations, not merely an ethical add-on.

A One Biology perspective emphasises that biological processes across levels, from microbial communities to whole animals and ecosystems, are interconnected and collectively shape sustainability outcomes. Y. Xie *et al.* (2022) highlighted that the rumen microbiome drives nutrient metabolism, feed efficiency, and methane emissions while influencing host physiology, illustrating how microbe-host dynamics underpin sustainable cattle performance. X. Liu *et al.* (2023) extended this view to soil-plant-animal microbiomes, demonstrating that microbial diversity supports ecosystem function, nutrient cycling, and resilience, providing a biological foundation for One Health and holistic sustainability. As shown in Figure 1, the making of a regenerative cattle production system is conceptualised through the integration of societal expectations into the complementary frameworks of One Health, One Welfare, and One Biology, emphasising the interdependence of animal, human, and ecosystem processes.



**Figure 1.** The making of a regenerative cattle production system

**Source:** created by the author

Overall, the convergence of the concepts of “One Health,” “One Welfare,” and “One Biology” demonstrated that animal welfare cannot be considered a peripheral component of sustainable livestock development, but must be integrated into the design and evaluation of the system. Welfare outcomes have a biological basis, are mediated by social factors, and are conditioned by environmental conditions, linking productivity, emission intensity, public trust, and ecosystem resilience within a single integrated system. Therefore, the regenerative cattle production model requires coordinated assessment tools that simultaneously consider health, behavior, microbiology, and socio-economic aspects. The inclusion of welfare in interdisciplinary, systemic management is a prerequisite for creating livestock systems that are scientifically sound, ethically justified, and environmentally sustainable in the long term.

### SUSTAINABILITY AND REGENERATION PRACTICES IN CATTLE PRODUCTION SYSTEMS: BEEF CATTLE

Beef cattle production occupies a central yet contested role in global food systems. The environmental footprint of beef cattle is characterised by multiple interacting pressures. C. Evangelista *et al.* (2024) quantified enteric methane as a dominant contributor to agricultural GHG emissions, while H. Guo *et al.* (2022) demonstrated that beef has one of the highest emissions intensities per unit of protein among livestock products. However, these emissions are part of a larger suite of environmental impacts that include land conversion, nutrient runoff, soil degradation and biodiversity loss. D.J. Eldridge *et al.* (2022) argued that focusing solely on carbon obscures these co-occurring pressures. Well-managed grazing systems can influence some of these outcomes positively. Strategic grazing, where cattle are moved across paddocks or pasture cells in ways that allow vegetation recovery and minimise bare ground, has been shown to improve or maintain soil health and reduce nitrate runoff compared with continuous grazing.

In beef systems, regenerative approaches typically involve rotational or adaptive grazing, integration with crop systems or silvopastoral designs, and management practices that encourage ecological flows. P.L. Peri *et al.* (2024) described regenerative grazing as a systems-based approach that reconnects livestock management with ecological processes. U. Khatri-Chhetri *et al.* (2022) found that rotational grazing reduced overgrazing and improved root development, while C.D. Morris (2021) highlighted its role in stimulating soil biological activity and manure distribution. While the precise outcomes depend on context, grazing that prevents vegetation from being consumed below critical thresholds can promote plant recovery and resilience. Systems thinking research further shows that improved grazing and manure management can create feedback loops. K.M. Brewer *et al.* (2023) demonstrat-

ed that better soil structure enhances forage quality, which improves cattle nutrition and productivity, while L.O. Tedeschi *et al.* (2024) linked these gains to improved economic performance and stewardship outcomes. Together, these positive loops showed how ecological and production goals can be aligned when cattle are managed as part of an integrated system rather than isolated production units.

One of the core regenerative claims is that cattle managed on permanent pastures can increase soil organic carbon and support broader ecosystem functions. Q. Zhang *et al.* (2023) reported that well-managed grazing improves soil structure, increases below-ground carbon storage and stimulates microbial activity essential for soil fertility. However, the magnitude and longevity of carbon sequestration from regenerative grazing remains debated. S. Ren *et al.* (2024) synthesised evidence showing that while soil carbon gains are possible, sequestration rates vary widely and are temporally limited. A.T. Simmons *et al.* (2026) documented measurable soil carbon increases under managed grazing, whereas K. Georgiou *et al.* (2022) cautioned that soils can reach saturation points, constraining long-term sequestration. Y. Wang *et al.* (2023), alongside S. Ren *et al.* (2024), argued that pasture-based sequestration alone cannot offset methane emissions but may contribute as part of a broader mitigation portfolio that also targets methane and nitrous oxide. Regenerative beef systems can also impact biodiversity and hydrological functions. Y. Wang *et al.* (2026) showed that managed grazing regimes that limit compaction and maintain permanent, diverse plant cover enhance habitat heterogeneity and ecosystem resilience. Regenerative practices can also improve hydrological performance. T.F. Döbert *et al.* (2021) demonstrated that restored soil structure increases infiltration capacity, while G. Agunbiade *et al.* (2025) found that improved plant cover reduced runoff and erosion, contributing to drought resilience and reduced reliance on irrigation.

Adoption of regenerative practices in beef systems is influenced by socio-economic drivers and policy contexts. C. Moisés *et al.* (2025) showed that incentives such as carbon markets, certification schemes and emissions reporting frameworks can motivate farmers to document and adopt soil- and ecosystem-enhancing practices. C. Early (2025) highlighted Brazil as a case where pasture improvement, agroforestry integration and methane-reducing feeds are being trialled to reduce deforestation while enhancing productivity. However, C. Moisés *et al.* identified gaps in technical knowledge, high initial costs, and limited access to finance as major barriers, especially for smallholder farmers.

Sustainable development and restoration of beef cattle farming systems depend on moving beyond the assessment of individual issues and recognizing cattle as an active component of agroecosystems. Evidence showed that adaptive grazing, nutrient cycling,

biodiversity enhancement, and soil management can deliver additional environmental and production benefits, but results remain dependent on specific conditions and cannot be considered universal. Soil carbon sequestration and improved ecosystem services can make a significant contribution to mitigation and resilience, but they do not eliminate the need to directly address methane and other greenhouse gas emissions. Therefore, the long-term sustainability of beef cattle systems requires integrated environmental management combined with a supportive policy framework, economic incentives, and robust monitoring that aligns environmental management with viable farm livelihoods.

### SUSTAINABILITY AND REGENERATION PRACTICES IN CATTLE PRODUCTION SYSTEMS: DAIRY CATTLE

Regenerative dairy farming shares similarities with regenerative beef farming but also exhibits distinct characteristics, as summarised in Table 1. The dairy cattle sector faces substantial sustainability challenges. R.W. McDowell *et al.* (2022) identified dairy systems as among the leading contributors to agricultural GHG emissions. A comprehensive understanding of dairy sustainability, therefore, must extend beyond simple productivity metrics. M. Bojovic & A. McGregor (2023), who emphasised regenerative capacity and social equity as essential components of long-term dairy system viability.

**Table 1.** Comparative table of regenerative beef and dairy cattle production systems

Aspect	Regenerative beef systems	Regenerative dairy systems
Production focus	Typically, on extensive or semi-intensive pastures.	Usually pasture-based or mixed crop-livestock systems.
Grazing management	Rotational/adaptive grazing, silvopastoral integration, strategic forage recovery.	Rotational grazing, forage diversification, integration with cover crops or forage crop rotation.
Animal welfare	Emphasis on natural behaviours, reduced stocking stress, improved longevity and health.	Pasture access, improved housing, lameness prevention, metabolic and reproductive health management.
Feed efficiency	Optimised through forage quality, supplementation, and adaptive grazing.	Balanced diets, pasture quality, supplementation, feed monitoring, and reduced metabolic stress.
Environmental outcomes	Soil carbon accumulation, improved soil structure, nutrient cycling, biodiversity enhancement, water infiltration.	Soil carbon retention, nutrient recycling through manure, reduced synthetic fertiliser use, enhanced biodiversity in pastures.
Green house gas mitigation	Partial offset via soil carbon; methane reduction achieved via improved forage quality, animal health, and genetics.	Partial offset via soil carbon; reduced emissions intensity per litre of milk through improved feed efficiency and animal welfare.
Biodiversity impacts	Increased habitat heterogeneity, pollinator support, microbial diversity.	Enhanced pasture flora diversity, improved soil microbiome, support for beneficial insects.
Socio-economic aspects	Often more suitable for smallholders or marginal lands; requires knowledge-intensive management; influenced by carbon markets and regenerative certification.	Requires infrastructure for milk collection/processing; knowledge-intensive; economic viability supported by productivity and ecosystem service incentives.
Resilience & sustainability	High resilience to drought and marginal lands if properly managed; multifunctional landscapes.	Resilient systems, diversified forage, integrated crop-livestock rotations; reduces reliance on external inputs.

**Source:** compiled by the author

One of the perennial sustainability concerns in dairy production is its environmental footprint. J. Heron *et al.* (2022) demonstrated through life cycle assessment that enteric methane from ruminal fermentation constitutes a major share of dairy GHG emissions, while C. Galloway *et al.* (2024) showed that the magnitude of these emissions varies widely across regions and management systems. Pasture-based systems generally produce GHG emissions in the range of ~0.8 to 1.7 kg CO<sub>2</sub>-eq/kg of fat- and protein-corrected milk. These studies consistently identified enteric methane and manure management as dominant emission sources, while also showing that herd productivity, feed quality and analytical boundaries strongly influence reported outcomes. Environmental impacts extend beyond climate change. R. Hu *et al.* (2024) demonstrated that dairy manure and fertiliser application are major sources of nitrogen and phosphorus losses to water bodies,

while A.B. Leytem *et al.* (2021) linked pasture and feed-crop mismanagement to soil degradation. Together these impacts revealed the tightly coupled nature of dairy production and ecosystem processes, supporting the conclusion that sustainability assessments must address multiple impact categories rather than rely on single indicators.

Animal welfare is a key sustainability dimension in dairy systems, and welfare outcomes are increasingly integrated into dairy research and practice. A.B. Petrean *et al.* (2024) found that pasture access and well-designed housing systems reduce lameness and improve cow comfort. Systematic reviews by M. Verdon *et al.* (2025) showed a substantial increase in pastoral dairy welfare research, particularly in nutrition, behavioural expression and environmental conditions. These authors converged on the conclusion that healthy cows with good welfare status exhibit higher lifetime productivity and

longevity, reduce resource use per unit of output, and experience lower disease burdens, aligning welfare improvements with One Health objectives. Regenerative agriculture seeks not just to sustain current conditions but to restore and strengthen ecological function. L.M. Alderkamp *et al.* (2025) documented a growing application of regenerative principles in pasture-based and mixed crop-livestock dairy systems. Although the academic literature on dairy-specific regenerative agriculture remained emergent, these authors emphasised that ecological benefits depend strongly on local adaptation and management context.

Regenerative dairy practices include rotational grazing, cover cropping, crop rotations, integration of livestock with arable production, and reduced external inputs. B. Emmett *et al.* (2025) described these practices as mechanisms for enhancing soil organic matter and system resilience. Empirical studies by S. Zhu *et al.* (2024) showed that such practices increase microbial diversity, improve water infiltration, reduce erosion and support habitat provision. D. Finlay (2024) argued that these outcomes represent a shift from extractive dairy production toward landscape-level regeneration. For example, O. Obasoro *et al.* (2025) demonstrated that mixed-species pastures increase biological nitrogen fixation via legumes, reduce dependence on synthetic fertilisers, and enhance soil structure and carbon stocks. X. Niu *et al.* (2025) further showed that improved soil biodiversity, including beneficial microbes and earthworms, enhances nutrient cycling and reduces nutrient runoff risks. Together, these studies illustrated that dairy cattle integrated into diversified landscapes can contribute positively to ecosystem services rather than degrade them.

Dairy farms that prioritise regenerative practices can also support biodiversity outcomes. A. Sher *et al.* (2024) found that managed grazing supports mosaics of plant communities that benefit invertebrates, pollinators and soil organisms. S. Lv *et al.* (2024) showed that increasing grassland diversity through rotational grazing and forage diversification maintains habitat complexity and strengthens ecological networks. These outcomes are consistently more favourable in grass-based systems than in confined systems, particularly where permanent pastures are maintained. Linking livestock to landscape function also entails improved nutrient flow management. Z.K. Al-Musawi *et al.* (2025) demonstrated that recycling dairy manure within crop rotations improves soil fertility and reduces reliance on synthetic fertilisers, thereby lowering eutrophication risks in adjacent water bodies.

Adopting regenerative and sustainable dairy practices is influenced by economic and policy frameworks. E. Bull *et al.* (n.d.), through the Regen Dairy project, illustrated how collaboration between farmers and global food companies can co-develop farmer-centric regenerative models that enhance biodiversity while

maintaining productivity and profitability. These authors emphasised that regenerative dairy must be locally adapted and embedded within whole-system response to climate, biodiversity and food security challenges. However, E. Bull *et al.* identified upfront transition costs, infrastructure requirements and knowledge gaps as major constraints, particularly in the absence of strong market incentives. They argued that policy instruments such as payments for ecosystem services, certification schemes, carbon markets and targeted research support are critical for scaling regenerative dairy practices. While regenerative approaches offer pathways to enhance ecological integrity, Y. Wang *et al.* (2023) cautioned against overstating their climate mitigation potential. Authors showed that soil carbon sequestration is context-dependent and subject to saturation, and that gains from regeneratively managed pastures do not fully offset enteric methane emissions. Consequently, these authors concluded that regenerative practices must be integrated with methane mitigation strategies, improved genetics, manure management and enhanced feed efficiency to achieve meaningful sustainability outcomes.

Taken together, the evidence suggests that the future sustainability of dairy systems hinges on improving biological efficiency rather than simply reducing scale or intensifying inputs. Dairy cattle convert human-inedible biomass into high-value nutrients, and when embedded within diversified crop–livestock systems, they can close nutrient loops and stabilise agroecosystem functioning. At the same time, unresolved trade-offs between productivity, methane emissions, nutrient leakage and welfare performance highlight the need for transparent, multi-criteria evaluation frameworks. The transition toward regenerative dairy therefore represents not a single practice shift, but a systemic redesign that aligns metabolic efficiency, ecological restoration and socio-economic viability within regionally adapted production models.

#### **REFRAMING SUSTAINABILITY IN CATTLE PRODUCTION SYSTEMS: BEYOND SINGLE METRICS. METHANE EMISSIONS**

This review revealed that sustainability in cattle production cannot be adequately assessed through isolated indicators such as GHG emissions or land-use efficiency alone. While methane emissions from enteric fermentation remain a legitimate concern, an exclusive focus on methane, risks overshadowing the broader biological, ecological, and socioeconomic roles of cattle within agroecosystems. The evidence reviewed supports a reframing of sustainability as a multidimensional framework containing aspects of environmental integrity, animal welfare, system productivity, economic viability, and social legitimacy. Cattle, as ruminants, occupy a distinct niche in food systems by converting fibrous biomass into high-quality human nutrition while

interacting dynamically with soils, plants, and microbial communities. Sustainability outcomes, therefore, depend less on the mere presence of cattle and more on how, where, and within which management frameworks they are integrated. This systems perspective is increasingly aligned with regenerative and agroecological paradigms, which emphasise functional outcomes, such as soil health, biodiversity, and resilience, rather than narrow efficiency metrics.

Methane mitigation remains a critical component of climate strategies for cattle systems, but its interpretation requires nuance. Enteric methane represents an energetic loss to the animal and is influenced by diet composition, rumen function, health status, and overall management. I. Kyriazakis *et al.* (2024) demonstrated that improvements in feed efficiency and forage quality reduce methane emissions per unit of output, while S. Malyugina *et al.* (2025) showed that animal health and longevity further lower emissions intensity by spreading production over a longer productive lifespan. These studies consistently indicated that methane reductions often emerge as co-benefits of welfare-oriented and regenerative management, rather than as outcomes of emission-targeted interventions alone. Short-lived climate pollutants such as methane also differ fundamentally from carbon dioxide in atmospheric behaviour, revealing the importance of temporal and systems-level perspectives when evaluating climate impacts. The reviewed evidence supported the position that methane mitigation should be embedded within integrated strategies that enhance biological efficiency and ecosystem function rather than pursued as a stand-alone objective.

A central finding of this review was that animal welfare functions not merely as an ethical consideration but as a critical driver of sustainability outcomes. J.L. Capper & P. Williams (2023) showed that poor welfare, manifested through chronic stress, disease, or lameness, reduces productivity and increases resource use per unit of output, while T.S. Winton *et al.* (2024) linked welfare deficits to reduced system resilience. Conversely, systems that prioritise cattle welfare consistently demonstrate improvements in longevity, reproductive performance, feed efficiency, and emissions intensity. The integration of welfare within sustainability frameworks is strengthened by the One Welfare concept, which explicitly links animal welfare, human well-being, and environmental integrity. A. Diana *et al.* (2020) provided early empirical evidence that welfare-positive systems reduce disease prevalence and antimicrobial use, while L. Boyle & P. Stevenson (2025) demonstrated links between improved animal welfare, farmer satisfaction and mental health. S. Platto *et al.* (2025) synthesised this evidence to argue that welfare improvements often generate simultaneous benefits across animal, human and environmental domains. Despite these links, the authors collectively noted that welfare remains

inconsistently incorporated into sustainability assessment tools, suggesting a need for more comprehensive indicators that capture animal-based measures alongside environmental and economic metrics.

In regenerative contexts, welfare gains often emerge indirectly through management practices such as pasture access, adaptive grazing and reduced stocking stress. These approaches enable cattle to express natural behaviours, including grazing, social interaction and movement, while reducing the chronic pressures associated with confinement or overstocking. Improved comfort and behavioural freedom are commonly linked with better hoof condition, lower stress levels and improved overall health status. At the same time, these management strategies support vegetation recovery and soil function, illustrating that animal well-being and environmental performance can develop in parallel.

#### **REGENERATIVE CATTLE PRODUCTION SYSTEMS: POTENTIAL AND CONSTRAINTS**

Regenerative beef production systems demonstrate clear potential to improve soil health, biodiversity, and nutrient cycling when grazing is well managed. J. Mehre *et al.* (2024) reported that rotational and adaptive grazing enhance soil structure, promote perennial root systems and stimulate microbial activity, while A.T. Simmons *et al.* (2026) linked these changes to improved long-term productivity. These outcomes are particularly relevant in regions where beef cattle utilise marginal lands unsuitable for cropping, reinforcing their role in multifunctional landscapes rather than purely extractive production systems. However, the climate mitigation potential of regenerative beef systems remains contested. C. Rousset *et al.* (2024) cautioned that soil carbon sequestration rates are highly context-dependent and may plateau over time, limiting long-term mitigation potential. While soil carbon gains can partially offset emissions, the evidence consistently suggests that regenerative grazing alone is unlikely to render beef production climate-neutral. This reveals the importance of avoiding overgeneralised claims and instead adopting transparent, site-specific assessments.

Beyond carbon, regenerative beef systems contribute meaningfully to biodiversity conservation, hydrological regulation, and landscape heterogeneity. These benefits are often absent from conventional life cycle assessments, yet are central to ecosystem sustainability. Socio-economic factors, including access to knowledge, finance, and supportive policy instruments, remain decisive in determining adoption rates, particularly among smallholders. Scaling regenerative beef production, therefore, requires institutional support alongside scientific validation. Dairy production presents distinct sustainability challenges due to its intensity, nutrient flows, and reliance on high productivity per animal. Nevertheless, R. Teague & U. Kreuter (2020) showed that regenerative principles can be successfully

applied to dairy systems, particularly in pasture-based and mixed crop-livestock contexts. Practices such as rotational grazing, forage diversification, cover cropping, and integrated manure management can enhance soil health, reduce nutrient losses, and improve biodiversity outcomes. Animal welfare plays a particularly salient role in dairy sustainability. As with beef systems, regenerative dairy practices should not be viewed as a singular climate solution. Y. Wang *et al.* (2023) showed that soil carbon sequestration contributes to mitigation but does not negate the need for methane-reducing feed additives, genetic selection for efficiency and precision nutrient management. The emerging consensus is that regenerative dairy systems are most effective when embedded within holistic sustainability strategies rather than promoted through simplified climate narratives.

Overall, regenerative cattle production systems offer a credible pathway to enhance ecological function, animal welfare and system resilience, but their benefits are conditional rather than automatic. Outcomes depend on context-specific management, realistic expectations regarding carbon sequestration, and integration with complementary mitigation strategies targeting methane and nutrient losses. Both beef and dairy sectors demonstrate that regeneration is most effective when embedded within multifunctional landscape management and supported by coherent policy and economic frameworks. Long-term credibility therefore requires transparent measurement, interdisciplinary governance and alignment between environmental goals, productivity and farmer livelihoods.

#### **SOCIETAL EXPECTATIONS, POLICY, AND SYSTEM LEGITIMACY: FUTURE RESEARCH DIRECTIONS**

The long-term viability of cattle production systems is increasingly shaped by societal expectations regarding environmental responsibility, animal welfare, and transparency. F. Mata & I. Domingues (2025) argued that public trust depends not only on emissions reductions but also on visible commitments to ethical animal treatment and land stewardship. Regenerative and welfare-oriented systems may therefore enhance social licence by aligning production practices with consumer and policy priorities. Policy frameworks that reward ecosystem services, welfare outcomes, and verified sustainability performance are likely to be pivotal in supporting transition pathways. Carbon markets, regenerative certification schemes, and payments for biodiversity or water regulation services offer potential mechanisms but require robust, standardised metrics to avoid greenwashing and ensure credibility. Importantly, farmer livelihoods must remain central to these frameworks; sustainability transitions that undermine economic viability risk low adoption and social resistance.

Despite the rapid growth of literature on sustainable and regenerative cattle production, important knowledge gaps persist that limit robust system-level

evaluation and effective policy alignment. Addressing these gaps is essential for positioning cattle systems within global sustainability agendas, including the United Nations Sustainable Development Goals (SDGs) (United Nations, 2026). The research community should aim for long-term, integrated experimental research that simultaneously evaluates productivity, GHG emissions, soil carbon dynamics, biodiversity, nutrient cycling, and animal welfare. Most current studies focused on isolated indicators or short time frames, which constrains their relevance to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Long-term trials are particularly important for assessing the durability of soil carbon sequestration and ecosystem service gains, given growing evidence of saturation limits and vulnerability to climate variability. Coordinated research networks across agro-ecological zones would improve the robustness and comparability of sustainability claims. Future research must also explicitly integrate animal welfare into sustainability assessment frameworks, aligning livestock research with SDG 3 (Good Health and Well-Being) and SDG 12. While substantial evidence links improved welfare to enhanced productivity, longevity, and reduced emissions intensity, welfare indicators are rarely embedded within life cycle assessments or whole-farm sustainability models. Developing standardised, animal-based welfare metrics that can be incorporated alongside environmental and economic indicators would strengthen One Welfare approaches and improve the ethical credibility and societal relevance of sustainability evaluations.

Context-specific methane mitigation research remains a critical priority for SDG 13. Many mitigation strategies have been developed under confined or high-input systems, with limited validation in pasture-based, mixed, or regenerative cattle systems. Future research should assess how dietary strategies, grazing management, rumen microbiome function, and genetic selection interact under diverse production contexts, while also considering impacts on animal health and welfare. Emphasis should be placed on mitigation approaches that deliver co-benefits for productivity and resilience, rather than narrowly targeting methane reduction alone. Soil carbon and ecosystem service research must move beyond offset-centric narratives to support SDG 15 (Life on Land) and SDG 6 (Clean Water and Sanitation). While regenerative grazing and integrated crop-livestock systems can enhance soil organic carbon, water infiltration, nutrient retention, and biodiversity, reliance on soil carbon sequestration as a long-term offset for ruminant emissions carries substantial risk. Future studies should therefore prioritise realistic assessments of sequestration potential, permanence, and trade-offs, while placing greater emphasis on multifunctional ecosystem outcomes rather than single carbon metrics.

Social and economic dimensions of system adoption require far greater research attention to support SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities). Farmer decision-making is influenced by labour requirements, financial risk, knowledge access, market structures, and policy incentives, yet these factors remain underrepresented in biophysical studies. Comparative and participatory research approaches are needed to identify region-specific barriers and enablers of adoption, particularly for small- and medium-scale producers whose livelihoods are closely tied to cattle production. Future research should also address policy coherence, governance, and sustainability assessment methodologies, directly contributing to SDG 17 (Partnerships for the Goals). Aligning climate mitigation targets, agri-environmental schemes, animal welfare regulations, and market-based instruments is essential to avoid incentivising narrow techno-fixes or unintended environmental and social trade-offs. Advances in systems modelling, interdisciplinary assessment frameworks, and stakeholder-engaged research will be critical for evaluating cattle production as a dynamic component of agro-ecosystems rather than solely as a source of emissions.

Cattle production systems interact directly with multiple dimensions of the SDGs, including food security, climate action, ecosystem integrity, human well-being, and rural livelihoods. Because cattle systems simultaneously influence nutrition provision (SDG 2), greenhouse gas emissions (SDG 13), land and water resources (SDGs 6 and 15), animal and human health (SDG 3), and socio-economic resilience in rural communities (SDGs 8 and 10), they represent a critical leverage point for achieving integrated sustainability outcomes. Explicitly linking future cattle research to the SDGs is therefore essential for ensuring that scientific advances inform policy, guide investment priorities, and support coherent, systems-based transitions rather than fragmented or single-issue interventions. Embedding SDG alignment within research agendas also strengthens the societal relevance, legitimacy, and global comparability of sustainability assessments in cattle production.

### CONCLUSIONS

Beef cattle sustainability and regeneration interact actively. Regenerative beef systems offer pathways to integrate ecological restoration with productive agriculture, enhancing soil health, promoting biodiversity, supporting water function, and increasing resilience, but they are not a universal solution. Outcomes

depend on how cattle are managed, where they are kept, and how human and ecological needs are balanced. Achieving meaningful sustainability in beef production thus demands system-level, evidence-based assessments that embrace both environmental and regenerative principles, recognising cattle as part of dynamic agroecosystems rather than discrete production machines. Sustainability and regeneration in dairy cattle systems require holistic, systems-level approaches that integrate environmental, animal welfare, social and regenerative principles. Dairy systems must be evaluated not only for their productivity but for their ecological contributions, such as soil carbon, biodiversity, water quality, nutrient cycling, and for their socio-economic resilience. Appropriately managed, regenerative dairy cattle systems can transition from being a source of environmental pressure to co-designers of healthier agroecosystems, though this depends on context, management quality and supportive policy frameworks.

This review supported the conclusion that cattle can contribute to sustainable and regenerative agricultural systems when managed within integrative frameworks that prioritise biological function, animal welfare, and ecosystem health. Methane mitigation remains necessary but insufficient as a singular goal. Instead, sustainability gains emerge most consistently where welfare-positive management, regenerative practices, and system optimisation converge. Advancing such systems will require robust science, transparent metrics, supportive policy, and recognition of cattle as active participants in complex agro-ecosystems rather than solely as sources of environmental burden. Continued rigorous research and transparent assessment frameworks are essential to understand the regenerative potential of both beef and dairy systems and to guide science-based decision-making. Future research priorities should address the need for integrative, long-term, and context-specific evidence to support cattle production systems that contribute meaningfully to multiple SDGs, balancing food provision, environmental stewardship, animal welfare, and socio-economic resilience.

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### CONFLICT OF INTEREST

The author declares no conflicts of interest.

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## Сталі та регенеративні системи виробництва великої рогатої худоби: огляд літератури

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**Анотація.** Виробництво великої рогатої худоби залишається важливим для глобальних продовольчих систем через його зв'язок із продовольчою безпекою, впливом на довкілля, добробутом тварин та очікуваннями суспільства. Метою цього огляду було дослідити роль м'ясної та молочної великої рогатої худоби в стійких та регенеративних сільськогосподарських системах з використанням інтегрованого, системного підходу. Огляд базувався на критичному узагальненні рецензованої літератури, що стосується екологічних показників, викидів метану, добробуту тварин, регенеративних методів управління та соціально-економічних аспектів виробництва великої рогатої худоби. Було проаналізовано рамки сталого розвитку, що використовуються в системах вирощування великої рогатої худоби, з особливою увагою до обмежень однопараметричних оцінок, таких як викиди парникових газів. Було описано біологічні основи виробництва метану та його взаємозв'язок з ефективністю годівлі, здоров'ям тварин та управлінням. Були розглянуті докази щодо регенеративних практик у виробництві яловичини та молочних продуктів, включаючи управління випасом, динаміку вуглецю в ґрунті, результати біорізноманіття та цикл поживних речовин. Роль добробуту тварин була проаналізована через рамки «Одне здоров'я», «Один добробут» та «Одна біологія», підкреслюючи її інтеграцію з продуктивністю, інтенсивністю викидів та стійкістю системи. Були виявлені прогалини в поточних оцінках стійкості та методологіях досліджень, зокрема щодо довгострокової ефективності системи, показників добробуту та узгодженості політики. Результати цього огляду можуть бути використані дослідниками, політиками, консультантами та фермерами для підтримки розробки, оцінки та впровадження систем вирощування великої рогатої худоби, які поєднують продуктивність з раціональним використанням природних ресурсів та добробутом тварин

**Ключові слова:** агроєкосистеми; добробут тварин; викиди парникових газів; зменшення викидів метану; єдине здоров'я; єдиний добробут; регенеративне сільське господарство

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