Review

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Karun Kaniyamattam * , Megha Poyyara Saiju , Miguel Gonzalez

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Review

Data-Driven Strategic Sustainability Initiatives of Beef and Dairy Genetics Consortia: A Comprehensive Landscape Analysis of the US, Brazilian and European Cattle Industries

Karun Kaniyamattam [1]*, Megha Poyyara Saiju [1] and Miguel Gonzalez [2]

[1] Artificial Intelligence for Sustainable Livestock Systems Laboratory, Department of Animal Science, Texas A&M University

[2] USDA/ Foreign Agricultural Service

* Correspondence: karun.kaniyamattam@ag.tamu.edu

Abstract

The sustainability of the beef and dairy industry requires a systems approach that integrates environmental stewardship, economic viability, and social responsibility. Over the past two decades, global genetic consortia have advanced data-driven germplasm programs to enhance sustainability across cattle systems. These initiatives employ multi-trait selection indices aligned with consumer demands and supply chain trends, targeting production, longevity, health, and reproduction which include greenhouse gas mitigation, improved resource efficiency, operational safety, and optimized animal welfare as outcomes. This study analyzes strategic initiatives, germplasm portfolios, and data platforms from leading genetics companies in the USA, Europe, and Brazil. U.S. programs combine genomic selection with reproductive technologies such as *in-vitro* fertilization and sexed semen to accelerate genetic progress. European efforts emphasize resource efficiency, welfare, and environmental impact, while Brazilian strategies focus on adaptability to tropical conditions, heat tolerance, and disease resistance. Furthermore, mathematical models and decision-support tools are increasingly used to balance profitability with environmental goals, reducing sustainability trade-offs through data-driven resource allocation. Industry wide collaboration among stakeholders and regulatory bodies underscores a rapid shift toward sustainability-oriented cattle management strategies, positioning genetics and technology as key drivers of long-term resilience.

Keywords: beef and dairy sustainability; data-platforms; genomics; landscape analysis; reproductive programs

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1. Introductiol

The global beef and dairy production industries are encountering various challenges which include maintaining sustainability metrics, competitiveness amidst declining prices, rising costs, intense competition and increasing public scrutiny. These challenges require finding solutions that are sustainable, appropriate, technically feasible, cost-effective and publicly acceptable [1]. The transition to sustainable beef and dairy production is inevitable, regardless of the challenges. Multi-trait optimization of germplasm and advanced reproductive technologies offers a vital solution by addressing these challenges holistically. This approach enables the industry to achieve a balanced alignment of various objectives (Figure 1) including air and greenhouse gas emissions, land and water resources, employee safety, animal health and well-being, as well as efficiency and yield [2-5]. However, this multi-trait complex system optimization process will not happen spontaneously, rather must be coordinated with the policy implementation plans of governments, policymakers and NGOs [6]. Policymakers are increasingly called upon to evaluate the impact of their strategies and policies concerning sustainable development. This requires the use of agricultural systems decision models as tools and data for identifying and assessing the potential environmental, economic and social effects of different policy options [7]. Advances in computer modelling and artificial intelligence coupled with the complexity and interconnectedness of global sustainability challenges, will likely drive demand for credible, realistic, transparent and useful models, necessitating a multidimensional and interdisciplinary approach to their [8].

Our study aims to investigate sustainability-enhancing activities in the global beef and dairy industries through three objectives: (1) emphasizing the multi-trait nature of sustainability dimensions in the US, Europe, and Brazil (2) exploring the propagation of multi-trait optimized germplasm by cattle genetic consortia, aligned with dynamic sustainability metrics designed by stakeholders, including consumers; and (3) highlighting the need to integrate decision models and data-driven platforms to make informed decisions, ensuring continuous progress towards evolving sustainability targets..

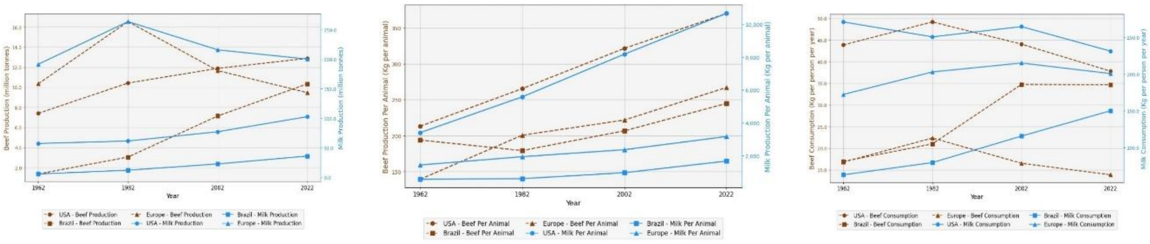
2. Regional Trends in Beef and Dairy Population, Production and Consumption Patterns in the USA, Europe and Brazil

Cattle production involves breeding animals to produce products such as meat, milk, and other dairy products for human consumption [9]. Beef and milk production faces challenges in balancing food needs and sustainable development, however new technologies can aid in optimal development and biodiversity conservation [10]. The USA, Brazil, and Europe are the three of the largest beef and milk-producing geographies globally. An analysis of historical and current trends in cattle population, beef production and milk production across the USA, Brazil and Europe from 1962 to 2022 reveals distinct regional patterns. Cattle production is one of the most important agricultural income sources in the United States, accounting for 18% ($66.2 billion) of the total cash receipts from agricultural commodities in 2019 [11]. In the USA, the cattle population peaked at 250.65 million in 1985 but declined to 87.2 million in 2024. According to the cattle report published by the National Agricultural Statistics Service (NASS), there are 28.2 million beef cows and 9.36 million dairy cows in the United States as of 2024. The Brazilian cattle industry showed a dramatic increase driven by intensified beef production and productivity gains. Similarly, Europe's cattle numbers declined from 197.9 million in 1962 to 113.22 million in 2022. These dynamic trends in cattle population highlight regional differences in cattle production and its economic and environmental impacts. The USA and Europe have experienced a decline in cattle numbers, yet their beef and milk production per animal have increased significantly, indicating advancements in productivity and efficiency.

According to Food and Agriculture Organization of the United Nations [12], beef production in the USA increased from 7.41 to 12.89 million tonnes over the decades from 1962 to 2022, Europe peaked at 16.56 million tonnes in 1982 before declining to 9.47 million tonnes in 2022, while Brazil steadily expanded from 1.36 to 10.35 million tonnes. Similarly, milk production rose in the USA from 57.27 to 102.75 million tonnes in 2022. It is peaked in Europe at 264.08 million tonnes in 1982 before decreasing to 200.44 million tonnes in 2022 and saw substantial growth in Brazil from 5.53 to 35.94 million tonnes from a period of 1962 to 2022, highlighting advancements in dairy farming (Figure 1a). Despite declining cattle numbers, beef productivity per animal increased significantly in the USA (213.20 to 370.30 kg) and Europe (139.4 to 267.20 kg) between 1962 and 2022, while Brazil saw a slower rise from 194 to 245 kg. Similarly, milk yield per animal improved dramatically in the USA (3,400.2 to 10,667.5 kg), Europe (1,428.4 to 3,164.9 kg) and Brazil (556.8 to 1,669.4 kg), reflecting advancements in dairy management and efficiency (Figure 1b). Even though Brazil has witnessed a substantial rise in cattle population (from 57.7 million in 1962 to 234.3 million in 2022) and total production, although its per capita beef and milk consumption remains lower compared to the USA and Europe.

Per capita meat consumption varies significantly across countries, often reflecting economic transitions and social-economic development trends. Globally, average per capita meat consumption has risen, indicating that meat production has grown faster than population growth [12]. Regardless of the fact that individuals in European and North American regions consume significant amounts of meat [13,14], per capita beef consumption declined in the USA (43.87 to 37.81 kg) and Europe (16.82 to 13.88 kg) from 1962 to 2021, while per capita beef consumption in Brazil has nearly doubled, with a rise of approximately 16.96 to 34.66 kg, reflecting a growing domestic market. There is a strong positive relationship between per capita meat consumption and average gross domestic product per capita: the richer a country is, the more meat the average person typically eats. Similarly, milk consumption decreased in the USA (271.14 to 231.39 kg) and Europe (172.28 to 200.74 kg), whereas Brazil experienced a significant rise (62.78 to 150.03 kg), indicating improved availability and dietary preferences (Figure 1c).

Globally, sustainable food and agriculture (SFA) play a crucial role in supporting all four pillars of food security such as availability, access, utilization, and stability, while also addressing the key dimensions of sustainability, including environmental, social and economic aspects [14].



(**a**) (**b**) (**c**)

Figure 1. The Changing Landscape of Beef and Dairy Production: Production Trends and Transformations Over Time [12] they are listed as: (a) Beef and Milk Production Across USA, Europe and Brazil (1962-2022); (b) Beef and Milk Production Per Animal in the USA, Europe and Brazil (1962-2022); (c) Per Capita Beef and Milk Consumption in the USA, Europe and Brazil (1962-2022).

3. Multidimensional Sustainability Analysis in Beef Production: insights from the USA, Europe and Brazil

Sustainability represents the state of a complex system that is always evolving, and it is an intrinsic characteristic of the system that needs to be constantly shaped and managed. The beef industry is improving sustainability through various assessment frameworks, stakeholder engagement, and increased transparency but needs to clarify the concept of sustainability and strengthen cooperation among national roundtables [15]. The multi stakeholder (including input from the United States National Cattlemen's Beef Association - NCBA) Global Roundtable for Sustainable Beef (GRSB) recently defined sustainable beef as a product that is socially responsible, environmentally sound, and economically viable. This definition emphasizes prioritizing the planet (focusing on natural resources, efficiency and innovation), people (including community well-being and food safety), animals (addressing animal health, welfare and efficient practices) and progress (encompassing natural resources, community, animal welfare, food quality and innovation) [16]. The sustainability of the beef industry encompasses a range of factors and provide a road map with interconnected actions that can support countries in selecting and prioritizing resources to accelerate the transition towards sustainable approaches (Figure 2). The numerous trade-offs between economic and environmental goals make it difficult to meet the challenge of sustainable beef production on a global scale [17]. Enhancing traditional husbandry practices and addressing welfare concerns through scientific investigations, practical solutions, consumer perceptions and educational tools can improve the beef industry's sustainability [18].

Global meat production had increased more than threefold by 1975, surpassing 350 million tonnes annually. The production of ruminant meat particularly beef is the agricultural commodity that contributes the most to the U.S. economy in terms of agricultural receipts. However, it is also the most dependent on natural resources and generates the highest environmental impact per kilocalorie or gram of protein among available food resources for the human population [19]. Protein nutraceuticals from highly mineralized collagen-containing beef raw materials have high amino acid potential making them a valuable source for specialized biologically active additives [20] and offers the potential to aid in reaching increased global protein needs [21]. The ruminant meat lipids provide heart-healthy cis-monounsaturated fatty acids and bioactive phospholipids, which can improve human health and contribute to global food security [22]. Furthermore, increasing genetic potential for marbling increases the likelihood of achieving higher yield and better-quality grade outcomes in commercial beef cattle [23].

Beef yield per animal has increased over time in the USA, Brazil and Europe due to advances in genetics, production and management practices and environmental management. Beef production in the USA is highly technology-driven, utilizing reproductive management strategies, genetic improvement technologies and various feed processing strategies to improve efficiency and cost of production [24]. Likewise, the European Union is the world's third-largest beef producer with strong production efficiency and adaptability driven by a diverse range of breeds animal types including cows, bulls, steers and heifers and various farming systems such as intensive, extensive, mixed breeders and feeders [25]. However, the European beef sector faces challenges in production efficiency, sustainability and animal welfare, necessitating new strategies and research to adapt to changing market demands and evolving research objectives [26]. Analogous to USA and Europe, sustainable beef cattle development in Brazil requires new digital technologies and sustainable supply chain management, with strategies that can promote human, environmental, and animal welfare [27]. As an example, the Sustainable Tension Index can help identify areas in the Brazilian pampa biome with potential for sustainable beef production, aiding decision-making for farm managers and politicians [28]. Intensive beef farming has expanded to the Brazilian Amazon where confinement practices have led to higher productivity rates and reduced deforestation [29]. This kind of productivity gains and land-saving strategies have significantly contributed to the growth in Brazilian beef production, reducing the need for extensive pasture expansion [30]. Diverse initiatives and dissemination of knowledge about sustainable practices in the beef chain is being implemented to provide a coordinated response of production, processing and distribution by multiple organizations, as they capitalize on market opportunities for sustainable livestock in Brazil [31]. Differences in beef production across countries reflect factors like natural resource availability, climate, population size, traditional culture and economic development [32]. Cultural and lifestyle differences influence sustainability of beef production in different regions [33]. In addition, vegetation and human demographics threaten the sustainability of regionally interconnected beef production systems. However, advancements in beef cattle production are necessary to secure the industry's future sustainability [21].

Beef cattle are one among the most important sources of atmospheric CH4 and mitigation of this gaseous emission has been highlighted as a tool to slow global climate change [34]. Production of 1 kg of beef used most land and energy and had highest global warming potential, followed by production of 1 kg of pork, chicken, eggs and milk [35]. The beef industry has come under scrutiny in recent decades over its perceived impacts on climate change from both climate scientists and the public [36]. Hence, climate change and animal welfare concerns demanded balanced breeding objectives and selection approaches for sustainable production-including health and longevity [37]. Tedeschi & Beauchemin [38] stated that U.S. beef cattle emissions account for about 2.2% of total anthropogenic greenhouse gas (GHG) emissions, equating to 22.6% of total US agricultural emissions. Feed additives could reduce these emissions by 5 to 15%, which aligns with efforts to improve the environmental sustainability of beef production. The U.S. beef cattle emissions have been reduced by about 30% from 1975 to 2021, and potential improvements in livestock and crop production systems could result in a 4.6% reduction in global CO2e emissions by 2030. Efforts to reduce the environmental impacts of beef production will likely be the strongest drivers of enhanced sustainability.

Carbon-reduced beef production, processing and trade techniques must be encouraged and supported to mitigate the effects of global warming and progress towards climate neutrality. The

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carbon footprint of beef production in Kansas, Oklahoma, and Texas is 18.3± 1.7 kg CO2e/kg carcass weight, with most of the footprint associated with the cow-calf phase [39]. According to USDA Meat Animal Research Center beef production system has decreased its carbon footprint by 6%, but its water footprint has increased 42% due to increased irrigated corn production [40]. Whereas beef production in Europe has a high potential for mitigating greenhouse gas emissions, with an average carbon footprint of 20.5 kg CO2 eq per kg carcass [41]. Beef cattle's carbon footprint varies between 8 and 22 kg CO2e per kg of live weight, with significant reductions in Canada, the US, Europe, Australia and Brazil over the last 30 years due to sustainable land management practices [42]. Minimising the carbon footprint of beef cattle through crossbreeding, genetic improvement and improved productivity per constant unit can effectively mitigate the effects of climate change [43]. Net beef GHG emissions can be reduced substantially via changes in management, with 46% reduction in net GHG emissions per unit of beef achieved using carbon sequestration management strategies on grazed lands and 8% reduction using growth efficiency strategies [44]. These initiatives prioritize preserving and enhancing carbon stocks in soils and landscapes. According to [45] soil sequestration has the highest mitigation potential in GHG emissions, with 80%, followed by growth enhancement technology (16%), diet modification (6%) and grazing management improvement (7%).

Efficient use of resources such as feed, water and land are critical for sustainable beef production with beef production being less efficient in converting natural resources into edible products compared to other livestock systems [4]. Organic beef production systems are slightly more profitable but have a higher impact on global warming and land use [5]. However, competition with other uses for land and water resources will also intensify, necessitating more efficient livestock production [46]. Numerous producers and farmers already make positive contributions to the environment to ensure that the beef value chain is a net positive contributor to nature. The global beef value chain manages natural resources responsibly and enhances ecosystem health [47]. The water use efficiency of each segment of the beef supply chain can be improved to reduce water footprint, by optimizing and integrating grazing systems (selecting water-efficient forage species like C4 plants), methods (utilizing precision agriculture techniques like soil mapping to optimize water use) and external inputs (optimizing fertilizer applications to increase dry matter production with less water requirements) to enhance ecosystem services, thereby decreasing the overall environmental impact of livestock production [48]. In many instances, producers are adopting land management practices to maintain soil health, increase carbon sequestration and optimize water usage efficiently [49]. A multi-indicator approach combining carbon and water footprints can provide a more comprehensive understanding of environmental impacts in beef cattle production systems [50]. Such strategies are developed to sustain and restore grazing lands, enhance resilience, conserve forests, grasslands and native vegetation, increase biodiversity and reverse ecological decline [51].

4. Innovations in Dairy Production: Enhancing Cattle Welfare, Genetic Improvements, Technological Advancements and Herd Management Strategies for Dairy Sustainability

Dairy production provides high-quality nutrients, animal welfare, and environmental sustainability while maintaining economic viability for dairy farmers [52]. Dairy herd turnover and sensible culling decisions improve profitability, welfare and sustainability [53]. Sustainability in the dairy industry involves achieving competitive growth and efficiency in dairy farming and processing, while ensuring environmental, economic and social aspects [54]. The dairy industry endeavors to harmonize environmental stewardship, economic sustainability and community well-being while adapting to evolving resources, technological advancements and consumer preferences. Sustainable dairy management practices should complement international perspectives from export markets, international organizations and dairy corporations. Sustainable agriculture hinges on emphasizing genetic diversity and resilience in dairy cattle, employing adaptive genetic improvement techniques and ensuring a consistent and accurate data flow [55].

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Strategic interventions can significantly improve dairy production in developing countries, addressing challenges like feed, management, health and food safety, contributing to meeting global demand and UN Sustainable Development Goals [56]. Leading dairy countries in the EU focus on implementing sustainability principles, focusing on environmental impact, animal welfare, health, and breed management issues [57]. Climate change may positively impact dairy cow production in Central Europe by potentially increasing fodder quantity through prolonged growing seasons and slight rises in ambient temperature and CO2 levels. However, mitigation strategies will be essential to ensure that adequate nutrition and maintenance of performance [58]. Brazil's dairy farming plays a vital role in the country's economy, with public policies supporting milk quality and safety. Dairy products contribute to daily intakes of selected nutrients of concern in Brazil, including 6.1-39.9% of daily energy intake, 7.3% of protein, 16.9% of saturated fat, 11.1% and 4.3% of total sugars and 10.2-37.9% of daily calcium, vitamin D, P, vitamin A and K, but mean daily consumption of 142 grams per person, equating to less than one typical portion per day below the 2006 Brazilian dietary guidelines, which recommend three portions of milk and dairy products daily [59]. However, its limited presence in the international market is primarily due to high production costs and lower milk quality [60]. There is a need for policies and practices that align with local and international expectations, particularly in the dairy industry of Brazil [61]. In Brazil, dairy farms face common welfare and production issues, such as subclinical mastitis and tick infestations, but also specific issues like lameness and hock injuries [62]. Sustainability objectives prioritize the well-being of dairy cattle by promoting the widespread adoption of optimal practices in disease prevention, treatment, management, stress resistance and selecting suitable genetics to promote better welfare outcomes throughout the production cycle. Large-scale dairy farms in Parana, Brazil, have greater economic, environmental, and social sustainability, making them more likely to survive in the medium and long term [63].

According to Borawski et al. [64] the U.S. milk market has experienced notable changes between 2009 and 2018. During this period, the number of dairy cows increased slightly by 2%, from 9.2 million to 9.4 million. However, milk yield per cow saw a significant rise of 13%, leading to a 15% overall increase in milk production. Despite this growth in production, per capita consumption of liquid milk decreased from 112 kg in 1975 to 66 kg in 2018, while total dairy product consumption per person increased from 244 kg to 293 kg over the same period. The life cycle assessment of the U.S. dairy industry in 2008 highlighted its environmental impact and by 2017, advancements in dairy farming practices had reduced water use by 30%, land use by 21%, and the carbon footprint by 19% per gallon of milk compared to 2007 [65]. The dairy industry aims to achieve GHG neutrality, optimize water use and improve water quality by 2050, with U.S. dairy farmers committed to enhancing soil health and protecting biodiversity [66]. Beef-on-dairy breeding strategies enhance profitability and sustainability in dairy production, and it is a potential solution to mitigating the GHG footprint of beef [67]. Increasing animal productivity, improving genetic potential and reducing herd size can significantly reduce GHG emissions from livestock production systems [68]. Beef production from dairy calves has lower environmental impacts than suckler herds, but sustainable management strategies are needed to improve environmental performance [69].

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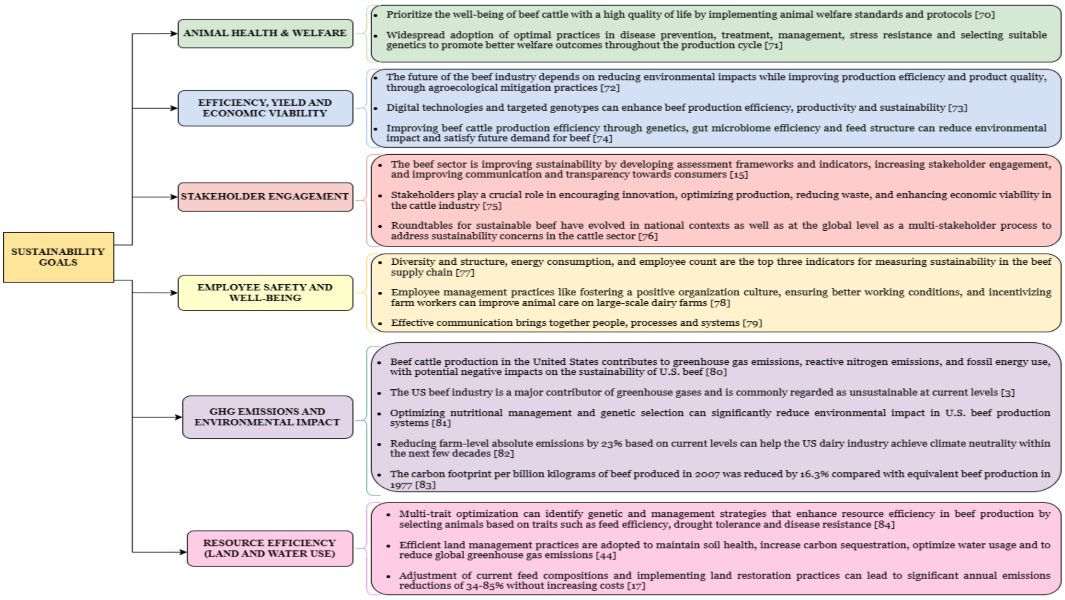

Figure 2: Sustainability goals pursued by the global beef and dairy industries. Multiple competing animal and environmental traits of interest are being optimized by cattle geneticists and production management experts (indicating an intense multi-trait optimisation approach)

5. Landscape Analysis of Genetic Consortia in the Beef and Dairy Industries of the USA, Europe and Brazil: Driving Sustainability Through Adaptive Genomic Selection Indices and Germplasm Innovations

Genomic information and genetic selection indices integrated into genetic evaluations significantly benefits traits linked to welfare and sustainable production of both beef and dairy systems. In the USA, several genomic selection indices are utilized by companies to enhance cattle breeding efficiency and profitability. ABS Global's Beef Advantage Index uses multitrait optimization to select beef sires for dairy operations, emphasizing traits crucial for reproductive success, growth, feed intake and carcass quality. Incorporating growth and carcass traits in breeding goals for combined dairy and beef production systems can improve profitability and increase self-sufficiency [85]. The Custom Index of ABS Global allows dairy producers to tailor genetics to their specific needs, leading to faster genetic progress and improved profitability. The EcoFeed Index by ST Genetics focuses on feed efficiency and environmental sustainability, targeting animals that maximize production while minimizing feed resources and GHG emissions. Novel monitoring systems to measure dairy cattle phenotypic traits can lead to more sustainable production with reduced environmental impact through reduced GHG emissions [86]. Zoetis offers the Dairy Wellness Profit Index (DWP$) focusing on maximizing productivity, efficiency, and sustainability across the dairy and beef industries. The Net Merit and Cheese Merit indices, developed by Select Sires and Alta Genetics, provide comprehensive tools for predicting profit potential in various milk markets, emphasizing key traits like milk yield, fertility and longevity (Figure 3). Refinement of selection indexes and breeding goals to emphasize traits related to animal welfare, health, longevity, environmental efficiency and overall resilience is enhancing sustainability and efficiency in dairy cattle [87].

In Europe, genomic selection indices are geared towards optimizing both productivity and sustainability. Viking Genetics' Nordic Total Merit Index (NTM) focuses on enhancing herd profitability and functionality by prioritizing health, reproduction and production traits. CRV's Health and Efficiency Indexes guide dairy farmers in improving herd health, fertility, and overall efficiency, leading to increased profitability and sustainability. Similarly, the NVI or Total Merit Index used in the Netherlands and Flanders integrates production, longevity, fertility, and cow health to guide breeding programs toward enhanced farm income and consumer acceptance. These

European indices place a strong emphasis on health and sustainability, aligning with regional goals of improving cattle welfare while boosting production (Figure 3).

In Brazil, genomic selection tools are pivotal in driving cattle production advancements and several companies in Brazil utilize specific selection indices to improve livestock genetics and enhance production efficiency (Figure 3). SEMEX Brazil employs the Methane Efficiency Index, which focuses on selecting animals based on their methane emissions efficiency, contributing to environmentally sustainable livestock production. Selection for lower-emitting phenotypes in dairy cattle can decrease the environmental footprint of dairy cattle products [88]. Methane intensity could be decreased by 24% by 2050 through the incorporation of CH4 production into breeding objectives [89]. However, genetic improvement in feed efficiency and reducing enteric methane production in replacement heifers can enhance the sustainability of beef cattle production [90], In particular, selecting for residual methane emissions holds significant potential, as it enables the breeding of low methane-emitting animals without negatively impacting other economically important traits [91]. Bell & Jauernik [92] argued for the inclusion of a customized profit and carbon total merit index as an effective tool for identifying sustainable milking cows and herd replacements, ultimately increasing profitability and reducing carbon emissions in commercial dairy herds. These methods maximize profit without compromising welfare [93]. ABS Pecplan company in Brazil utilizes the ABS Pecplan Selection Index, a comprehensive system designed to rank animals based on a combination of genetic and economic traits essential for the beef and dairy industries. Similarly, CRV Lagoa uses the Total Merit Index, an index that evaluates overall animal performance by incorporating multiple economic and genetic factors, ultimately aiming to improve herd efficiency and profitability. Additionally, CRV Health Indexes to improve dairy herd health and efficiency in Brazil, similar to Europe, ensuring that Brazilian farmers can produce healthier, more sustainable cattle while maintaining profitability. Brazilian genetic consortiums, including ABS Pecplan, CRV Brasil, and Semex Brazil emphasize multi-breed and indigenous cattle programs, particularly focusing on the integration of European and Zebu germplasm for tropical environments. These companies play a crucial role in advancing genetic selection and sustainable livestock production in Brazil.

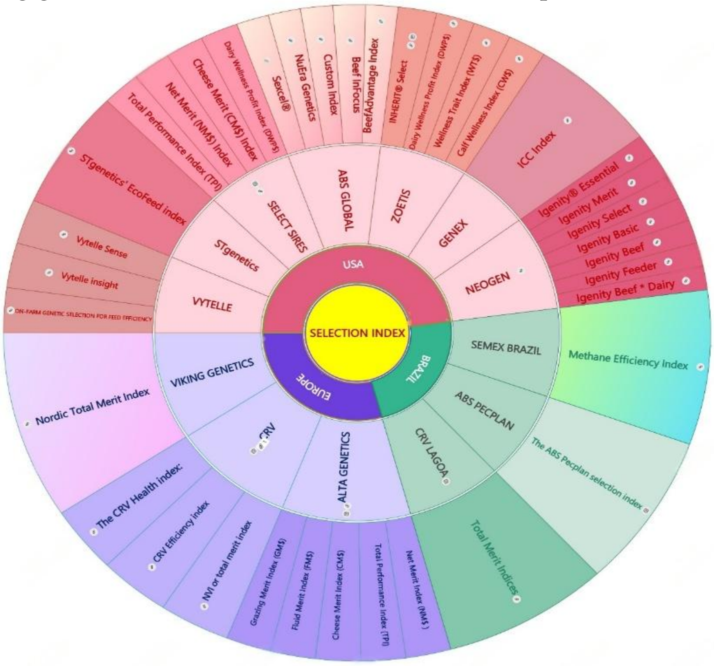

Figure 3: Genomic Selection Tools and Multitrait Optimized Selection Indices of genetic consortia in USA, Europe and Brazil, that is being periodically redesigned to contribute to the Sustainability aspirations of the cattle industry. Figure credits: https://www.edrawmind.com/app/editor/uArp5zpmZyJppxS3RLUBEqy1lvx0Yrsc

The figure 4 presents a variety of germplasm products offered by different genetic consortia across the USA, Brazil and Europe, focusing on enhancing cattle genetics for beef and dairy production. These products include multi-breed semen and embryos, with companies like ABS Global, Genex and CRV Brasil providing crossbreeding solutions to improve productivity and adaptability. Fertility and reproductive technology, such as in-vitro fertilized embryo transfer, is offered by companies like Vytelle to improve reproduction efficiency in both beef and dairy operations. Reproductive efficiency and health improvements are achieved through genomic selection and fertility-focused germplasm, leading to higher conception rates, reduced calving difficulties, and improved animal welfare. Targeted genetic solutions from organizations like Select Sires aim to maximize feed efficiency and reproductive success. Genetic programs and management changes can improve efficiency, sustainability and profitability of beef production by reducing feed used for maintenance and incorporating appropriate indicator traits in national cattle evaluation systems [94]. However, beef-on-dairy programs from ABS Global, Semex, and STGenetics introduce beef genetics into dairy operations to increase the value of dairy bull calves while maintaining dairy herd performance. Genomic testing-based selection from companies like Zoetis helps producers make informed breeding decisions, enhancing genetic diversity, productivity and supporting precision breeding strategies for sustainable and profitable cattle production.

The sustainability outcomes of these genetic programs focus on economic viability, climate-smart solutions, enhanced herd health and optimized production systems. Additionally, evaluating genetic resistance to disease, climate tolerance and resilience associated traits are being used as objective, measurable phenotypes or as suitable biomarkers [95] for genomic selection in beef and dairy cattle. Companies like ABS Global and STGenetics emphasize economic profitability and feed efficiency through accelerated genetic progress and improved herd management. Genomic selection based on data sources from new precision livestock technologies; that is data-drive phenotyping strategies can improve feed efficiency and upgrade sustainability in dairy cattle [96], especially by focusing on fitness, health, welfare, milk quality [97]. While companies like Select Sires and Zoetis highlight multi-trait optimization to ensure breeding decisions align with economic and environmental sustainability. Climate-smart and resource-efficient livestock systems are supported by genetic programs like ABS Global's BeefAdvantage Index, which ensures optimal beef protein supply while reducing resource waste and VikingGenetics' Nordic Total Merit Index, which incorporates 90 economically important traits for multidimensional sustainability goals. Companies like Vytelle and ABS Pecplan provide data-driven reproductive solutions to enhance supply chain transparency and genetic health. Data-driven decision-making for long-term sustainability is emphasized by companies like AltaGenetics, which use genomic data to ensure optimized breeding strategies that align with long-term sustainability goals. Digital technologies and targeted genotypes can further improve productivity and overall sustainability in beef herds [73]. Customized solutions for different production systems are offered by Brazilian genetic consortia, including CRV Brasil and Semex Brazil, ensuring adaptability to various management conditions. Companies like CRV and Alta Genetics integrate farm management insights to create customized breeding programs suited to different environments.

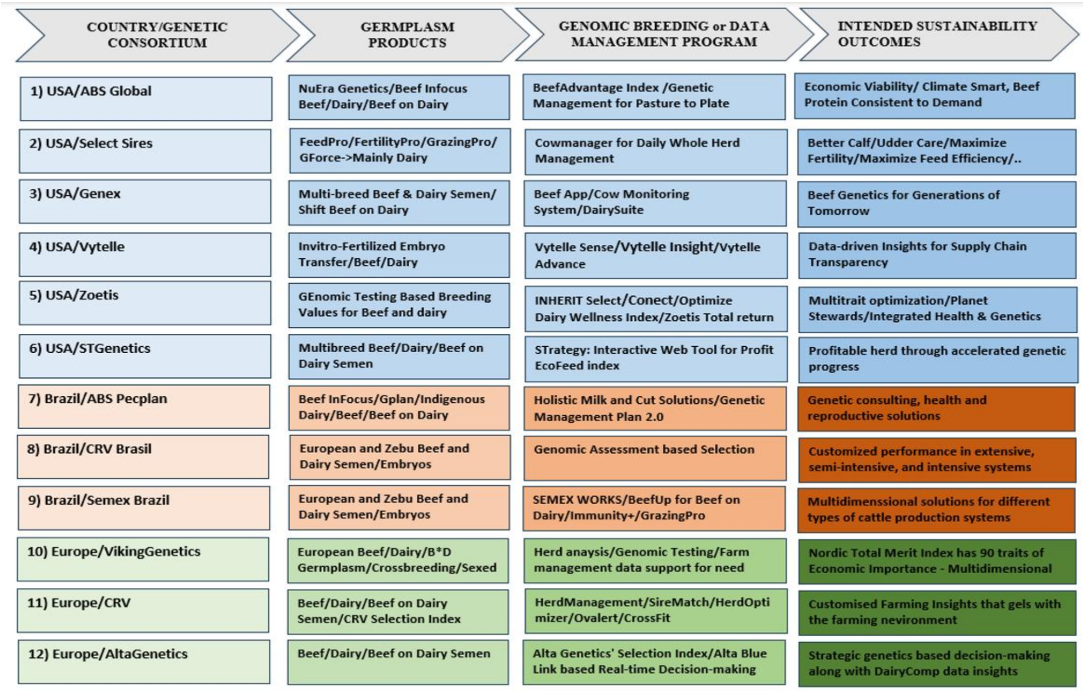

Figure 4: Global Genetic Consortiums in Cattle Breeding: Germplasm Products, Genomic Programs, and Sustainability Outcomes

6. Decision-Making for Beef and Dairy Sustainability: The Need for Systems-Level Food Value Chain Modeling

Agri-food chains are complex systems involving multiple firms and various modeling approaches can help evaluate decision-making and information flows in these complex systems [98]. Digital technologies that enable rapid capture and use of environmental and cattle performance data, even within extensive systems, enhance beef and dairy industry's productivity, efficiency, animal welfare and sustainability. These findings underscore the role of data-driven decision-making in modern animal breeding, enabling optimized livestock productivity while maintaining ethical and sustainable farming practices. The use of interactive web tools, herd monitoring and modelling platforms aids in providing customized farming insights, linking sustainability with economic and environmental resilience.

Mathematical modelling (MM) is the process of constructing computer models systematically and have a critical role in enhancing the sustainability of beef and dairy production by enabling the optimization of production processes, resource allocation and overall management strategies (Table 1). These models, which include linear programming, stochastic simulations and dynamic systems modeling, help producers make decisions by predicting outcomes under various scenarios, such as feed strategies, herd management and environmental impacts and operational efficiency of farming. The use of MM to facilitate research is consistently underutilized because potential users are not aware of the capabilities and benefits of MM, or they believe that model development is complex and difficult [99]. In the USA, the Integrated Farm System Model (IFSM) evaluates environmental and economic impacts of dairy farm practices, while the Cornell Net Carbohydrate and Protein System (CNCPS) optimizes ruminant nutrition. Meanwhile, in Brazil, the Linear Programming Mathematical Model helps optimize livestock-crop systems for sustainability. Brazil's Bioeconomic Model [100] and Linear Programming Mathematical Model [101] emphasize resource allocation and livestock health management, particularly in mixed crop-livestock systems. In the United States and Brazil, mathematical models have played a crucial role in optimizing cattle production systems. Simulation modeling can effectively evaluate the impact of policy-related decisions on interorganisational fairness in European food value chains, with potential applications in various food value chain case studies [102]. By integrating economic analysis, precision nutrition

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and environmental assessment, these models provide data-driven decision-making frameworks that support risk management, sustainable farm operations, and long-term profitability.

Mathematical nutrition models can assist in the discovery of the biological efficiency of mature beef cows [103]. Beef supply chain performance can be improved by using a model-driven decision support system based on system dynamics, projecting that optimizing beef weight and carcass percentage will reduce deficits and achieve a surplus by 2028, contributing to national food self-sufficiency [104]. Several models, such as the Farm Optimization Model: FARMDYN [105] and Optimization of Ruminant Farm for Economic and Environmental Assessment: Orfee of Europe [106], can simulate the cost of beef cattle production and analyse its environmental sustainability, aiding in risk management and profit management [107]. The MOLP (multi-objective linear programming) model effectively balances economic and environmental goals in beef logistics networks, highlighting the importance of distances and green tax incentives for sustainability [108]. Similarly, the MINLFP model (USA) and Linear Programming Model (Brazil) incorporate multi-objective optimization to balance these goals in beef logistics networks. These models aid in improving sustainability in European beef systems by incorporating economic, environmental and social sustainability metrics. Additionally, models like Pasture Simulation Model: PaSim [109] and the Nordic Feed Evaluation System (NorFor Model) [110] simulate pasture and feed interactions, optimize livestock production while assess emissions and carbon sequestration strategies. These approaches assist farmers in adopting precision agriculture techniques to enhance productivity while reducing the environmental footprint of cattle production. while USA models like the Dynamic Cattle Growth Model and Discounted Cash Flow (DCF) models evaluate profitability and cash flow in cow-calf operations. Additionally, the Brazilian Bioeconomic Model simulates the impact of tick infestations on beef systems, aiding in improved animal health and welfare. Integration of various data sources, random forests and linear regression models can accurately predict beef production and quality at the national level, aiding in sustainable livestock production [111].

Optimal design of dairy supply chains considering environmental and social aspects can lead to higher profits and lower economic costs, achieving social sustainability [112] like the DigiMilk model [113] which optimizes the dairy supply chain by integrating digital technologies to enhance traceability, resource efficiency and sustainability. Kristensen [114] suggested that a stochastic dynamic model for dairy cow production and food intake can predict income from milk, and calves, aiding in the development of a replacement model. Similarly, the Random Forest algorithm-based model predicts daily milk yield of dairy cows under heat stress conditions, enhancing sustainability and efficiency in the dairy sector [115]. The model proposed by Hassani et al. [116] optimizes resilience and sustainability in industrial dairy farms, increasing profitability and reducing environmental degradation. However, the Gamede model effectively explains differences in sustainability indicators between dairy farms, aiding decision-making and supporting resource-efficient production [117]. Shamsuddoha et al. [118] uses a system dynamics approach and simulation modeling to optimize dairy waste management and value addition, achieving sustainable outcomes for the industry and surrounding community. For instance, the Deterministic Whole Herd Simulation Model [119] and the Forage and Cattle Analysis and Planning (FORCAP) Model [120] focus on evaluating dairy herd management and dual-use forage systems to maximize profitability and sustainability. In dairy farming, European models like the Nordic Dairy Cow Model, Karoline optimize feeding by simulating digestion and metabolism, the Moorepark Dairy Systems Model (MDSM) enhances herd management for profitability and the DairyWise model improves farm sustainability by reducing disease risks, while the Financial and Renewable Multi-objective Optimization (FARMOO) Model integrates economic and environmental goals. Intrafarm simulation models focus on specific subsystems within a farm, such as nutrition, genetics, or reproductive management, while whole-farm simulation models take a systems-level approach, integrating multiple farm components including livestock, crops, labour, economics, and environmental factors to assess overall farm performance and sustainability. Whole farm systems models are an appropriate tool for developing and measuring GHG mitigation strategies in beef and dairy cattle production

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systems, with improvements in animal productivity and fertility potentially reducing emissions. Models can optimize nutrition, milk production, and reproductive strategies in dairy farming, while in the beef industry they assist in managing supply chains, evaluating economic sustainability and improving animal health and welfare. Combining multiple statistical analyses and investigating the purpose of the mathematical model is crucial for assessing their adequacy and usefulness for predictive purposes [122]. Ultimately, these models contribute to more efficient, sustainable, and profitable livestock operations..

Table 1. Simulation and Optimization Models for Sustainable Beef and Dairy Systems: Insights from the USA, Europe and Brazil

MODELS	PREDICTIVE VARIABLES AND SUSTAINABILITY OUTCOMES	REGION	FARM TYPE	METHODOLOGY AND SCOPE
	Economic Models			
Farm Model (FM) [123]	Evaluate dairy farm resilience by simulating production plan adjustments to adapt to external challenges and uncertainties	Europe	Dairy	Whole farm Optimization
Bio-Economic model implemented using GAMS (General Algebraic Modeling System) software [124]	Assess farmers' adoption of precision agriculture practices by evaluating its economic and biological impacts on Greek dairy cattle farms.	Europe	Dairy	Whole farm Optimization
ScotFarm [125]	Assess the financial vulnerability of Scottish dairy farms by simulating Johne's disease and payment support impacts to optimize economic resilience and sustainability.	Europe	Dairy	Whole farm Optimization
Dynamic stochastic simulation model [126]	Optimize dry period decisions in dairy herds by simulating impacts on milk production, cash flow, and emissions, accounting for farm variability.	Europe	Dairy	Intrafarm Simulation
Moorepark Dairy Systems Model (MDSM) [127]	Evaluate the financial performance of Holstein Friesian strains in different systems to identify the most profitable breeding and management strategies	Europe	Dairy	Whole farm Simulation
Dairy Farm Model [128]	Evaluate manure policy impacts on profitability, nutrient	Europe	Dairy	Whole farm Optimization

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	management, and emissions after milk quota abolition.			
A mathematical programming model [129]	Optimize dairy management to meet somatic cell count targets, improving milk quality and profitability while reducing mastitis control costs.	USA	Dairy	Intrafarm Optimization
A dynamic cattle growth model Discounted cash flow (DCF) models [130]	Evaluate profitability, risk, and cash flow in cow-calf operations by simulating cattle growth and financial performance to guide investment decisions.	USA	Beef	Intrafarm Simulation; optimization
The Forage and Cattle Analysis and Planning (FORCAP) model [120]	Simulate and evaluate the feasibility of dual-use forage systems in cow-calf operations to optimize management for profitability and sustainability.	USA	Beef; dairy	Whole farm Simulation
Bioeconomic model [100]	Simulate the economic and biological impacts of tick infestations on Brazilian beef systems to optimize management, reduce losses, and improve cattle health.	Brazil	Beef	Whole farm Simulation
A bio-economic farm model [131]	Assess the viability of conservation agriculture in Brazil's mixed crop-livestock systems by optimizing resource use for profitability and ecological resilience	Brazil	Beef; dairy	Whole farm Optimization
	Nutritional/Farm System Management Models			
DigiMilk model [113]	Optimize the dairy supply chain by integrating digital technologies to enhance traceability, resource efficiency, and sustainability in milk production and distribution.	Europe	Dairy	Whole farm Simulation
Pasture-Based Herd Dynamic Milk Model (PBHDM) [114]	Simulate and predict milk production in pasture-based dairy systems, considering herd size, pasture availability, and seasonal variations.	Europe	Dairy	Whole farm Simulation
Dairy Wise [132]	Simulate dairy farm processes to optimize herd management, improve profitability, and	Europe	Dairy	Whole farm Simulation

	reduce gastrointestinal nematode risk under varying conditions			
Multiscale agent-based simulation model of a dairy herd (MABSDairy) [133]	Simulate interactions between animals, herd dynamics, and management to optimize dairy herd health, productivity, and economic outcomes.	USA	Dairy	Intrafarm Simulation
Stochastic dynamic simulation modelling [134]	Evaluate reproduction and selection strategies in dairy herds to optimize performance and economic outcomes, considering farm uncertainty and variability.	USA	Dairy	Intrafarm Simulation
A multi-objective mixed-integer nonlinear fractional programming (MINLFP) model [135]	Optimize organic mixed farming by balancing profitability, resource efficiency, and sustainability through nutrient recycling.	USA	Beef; Dairy	Whole farm Optimization
	Farm System Management Models			
Mathematical model developed in the Czech University [136]	Optimize milking parlor performance by simulating management scenarios to enhance efficiency and profitability in dairy farms.	Europe	Dairy	Intrafarm Simulation
Moorepark Dairy Systems Model (MDSM) Pasture-Based Herd Dynamic Milk Model (PBHDM) [137]	Simulate pasture-based dairy systems to optimize herd management, maximizing milk production and profitability	Europe	Dairy	Whole farm Simulation
The mathematical model created in the Czech Republic [138]	Improve operational efficiency and economic performance by simulating different milking systems under farm-specific conditions.	Europe	Dairy	Intrafarm Simulation
The farm optimization model FARMDYN [105]	Simulate and optimize farm decisions by integrating economic, environmental, and social sustainability in European beef systems.	Europe	Beef; dairy	Whole farm Optimization & simulation

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Deterministic whole herd simulation model [119]	Optimize dairy herd management by simulating milking capacity, housing, and fat quota impacts on economics, productivity, and herd dynamics	USA	Dairy	Intrafarm Optimization
Organic Dairy Model [139]	Optimize forage and supplement use on southeastern U.S. organic dairy farms to enhance profitability, sustainability, and resource efficiency	USA	Dairy	Whole farm Optimization
	Nutritional Models			
Stochastic and dynamic mathematical model [140]	Simulate dairy farm performance under varying management and environmental conditions to optimize decision-making amid operational uncertainty.	Europe	Dairy	Intrafarm Simulation
Nordic Dairy Cow Model, Karoline [141,142]	Simulate digestion, metabolism, and nutrient use in dairy cows to optimize feeding and improve milk efficiency in Nordic systems.	Europe	Dairy	Intrafarm Simulation
Molley Model [143]	Simulate metabolic processes in lactating cows to optimize feeding and improve milk production efficiency.	USA	Dairy	Intrafarm Simulation
	Feed Optimization Models			
A feed pusher robot, designed and simulated using Simulink tools [144]	Automate feed pushing process to improve efficiency and reduce labour in dairy and livestock farms.	Europe	Dairy	Intrafarm Simulation
Linear Program Optimization (LPO) Model [145]	Optimize nutritional resource allocation in a dairy herd by minimizing feed costs while meeting dietary, health, and farm constraints efficiently.	Europe	Dairy	Whole farm Optimization;
Linear programming (LP) and weighted goal programming	Optimize dairy cow rations on organic farms by balancing feed costs, nutrition, and organic farming constraints	Europe	Dairy	Intrafarm Optimization

(WGP) techniques [146]				
Nordic Feed Evaluation System (NorFor Model) [110]	Optimize ruminant feeding by predicting nutrient needs and feed use to improve milk, meat production efficiency, and farm profitability.	Europe	Beef; dairy	Intrafarm Simulation
Rostock Feed Evaluation System [147, 148]	Assess nutrient supply and utilization in ruminants by modeling digestion to optimize feeding efficiency and improve livestock productivity and sustainability.	Europe	Beef; dairy	Intrafarm evaluation model with simulation components
A multi-period LP feed model [149]	Optimize dairy feed selection by evaluating economic and nutritional trade-offs over time to improve profitability and efficiency	USA	Dairy	Intrafarm Optimization
Farm-scale diet optimization model [150]	Optimize energy and protein efficiency in dairy diets to reduce land, water use, emissions, and enhance sustainability and profitability.	USA	Dairy	Whole farm Simulation
The Cornell Net Carbohydrate and Protein System (CNCPS) [151-154]	Predict ruminant nutrient needs by modeling digestion and metabolism to optimize diets for improved performance and efficiency	USA	Dairy; Beef	Intrafarm Simulation
Ruminant Nutrition System (RNS) [155]	Predict ruminant nutrient needs, intake, and performance, optimizing diets for productivity and sustainability	USA	Dairy; Beef	Intrafarm Simulation
	Environmental Models			
Financial and Renewable Multi-objective Optimization (FARMOO) Model [156]	Integrate economic profitability with environmental sustainability by maximizing financial returns, minimizing carbon footprint, and optimizing renewable energy in agricultural systems.	Europe	Dairy	Intrafarm Optimization

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HolosNor [157]	Assess mitigation strategies to reduce emissions intensity while maintaining or improving farm economic performance.	Europe	Dairy	Whole farm Optimization and simulation
Optimization of Ruminant Farm for Economic and Environmental assessment (Orfee) [106]	Optimize biotechnical and economic performance of mixed herds by balancing profitability and sustainability under different management strategies.	Europe	Beef; dairy	Whole farm Optimization
Pasture Simulation Model (PaSim) [109]	Simulate climate, soil, and pasture interactions to assess livestock production, emissions, and carbon sequestration under various management and climate scenarios.	Europe	Beef; dairy	Intrafarm Simulation
Integrated Farm System Model (IFSM) [158]	Simulate environmental and economic impacts of farm practices, focusing on sustainability metrics like emissions, nutrient cycling, and resource efficiency in grazing dairy farms.	USA	Dairy	Whole farm Simulation and optimization
N-CyCLES (nutrient cycling: crops, livestock, environment, and soil) [159]	Optimize nutrient cycling between crops, livestock, soil, and environment to reduce nutrient imbalances and enhance sustainability and profitability on dairy farms.	USA	Dairy	Whole farm Optimization
A linear programming mathematical model [101]	Optimize livestock-crop systems by efficiently allocating resources to maximize profitability while considering environmental sustainability	Brazil	Dairy	Whole farm Optimization
	Economic, Environmental and Feed Optimization Models			
Nonlinear multiobjective diet optimization	Optimize cattle feeding by minimizing costs and GHG emissions while maximizing productivity and nutritional efficiency	Europe	Beef	Intrafarm Optimization

7. Conclusions

The global beef and dairy industries are facing significant sustainability challenges, with a pressing need for innovative solutions to balance environmental, social and economic factors. Region-specific strategies are essential, as differences in resource availability, climate and economic conditions influence cattle production and sustainability outcomes in countries like the USA, Brazil, and Europe. Genomic selection, and multi-trait optimization have emerged as vital tools in achieving sustainable beef and dairy production by improving feed efficiency, reducing methane emissions and promoting animal welfare without compromising productivity. Additionally, the adoption of digital technologies, data-driven decision models and environmental monitoring systems enhances both operational efficiency and sustainability across various production environments. Mathematical models and decision support systems play a crucial role in optimizing cattle production systems, from logistics and herd management to environmental impact assessments. These models enable producers to make decisions by simulating outcomes under various scenarios, improving resource allocation and helping the industry navigate complex challenges. A coordinated approach that integrates scientific advancements, technological innovation and sustainable practices is necessary to meet the rising meat and milk demand and food security needs while reducing their environmental footprint.

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Abbreviations

The following abbreviations are used in this manuscript:

NASS	National Agricultural Statistics Service
SFA	Sustainable Food and Agriculture
GRSB	Global Roundtable for Sustainable Beef
GHG	Greenhouse gas
MM	Mathematical modelling
CNCPS	Cornell Net Carbohydrate and Protein System
MOLP	Multi-objective linear programming
FORCAP	Forage and Cattle Analysis and Planning
FARMOO	Financial and Renewable Multi-objective Optimization

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