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Advances in Nutrition and Feed Formulation Strategies for Sustainable Livestock Production

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Summary: Production of livestock is an important sector of worldwide agriculture as it helps to sustain food security, nutrition and rural livelihoods. Nevertheless, feed shortages, nutritional inefficiency and environmental effects are some of the long-term challenges experienced in the industry. The chapter talks about recent advances in nutrition and feed design that can be used to make livestock systems more sustainable. It emphasizes the need to utilize other feed such as agro-industrial by-products, aquatic plants, microbial proteins and insect meals to decrease the utilization of conventional grains and lower the competition with human food. Other roles of precision nutrition, computational modeling and least-cost formulation in optimizing nutrient utilization, reducing the cost of production and lessening environmental footprints are also discussed in the chapter. The use of innovative functional feed additives such as probiotics, enzymes, phytogenics and nanotechnology is proven to enhance the health, productivity, and quality of products in animals. It discusses the merger of nutrigenomics and precision livestock feeding as innovative solutions, which allows the development of a ration based on genotype and the delivery of nutrients in real-time. The problems of environmental sustainability are considered with the help of life cycle evaluations, circular feed economies and resource-efficient production systems. The need for an interdisciplinary collaboration, policy support and farmer involvement in the process of scientific advances into practical, resilient and sustainable livestock nutrition practices is also highlighted. These are innovations that lead to more productive, profitable and eco-friendly data-driven systems compared to the past, where the processes were based on constant input. Future research directions and the necessity of continuous innovation to fulfill the changing demands of sustainable livestock production are the last point of the chapter.
Keywords: Nutritional Strategies, Feed Formulation software, Sustainable Livestock Production

INTRODUCTION

Global agriculture is still dependent on livestock production as a fundamental source of nutritional food, income and food for millions of people. It is necessary to have effective and sustainable production systems to meet the increasing demand for animal-source foods in the global market and to support rural people. Meat, milk and eggs are the prominent sources of high-quality proteins, vitamins and minerals that are produced by cattle, sheep, goats, pigs and poultry. Other livestock advantages are improving soil fertility by recycling manure and promoting integrated agricultural systems (Smith et al., 2013).

The livestock industry globally injects close to 40 percent of the agricultural GDP and sustains over 1.3 billion people. Other than the economic worth, the sector supports food and nutrition security, rural employment and social stability. In other developing economies like Pakistan, livestock is the main component of the agricultural economy (around 63.6 percent of agricultural value addition and about 14.97 percent of national GDP) and sustains over eight million rural households (Rehman et al., 2017). This dependency on the economy emphasizes the importance of innovation in feeding and management practices to be productive and profitable. Nevertheless, the conventional feed materials are grains, forages, and oilseeds; a significant portion of the cereal grain is used by humans. Thus, livestock tend to feed on agro and their products like rice bran, wheat bran, paddy straw, barley, sorghum, and millet. Although economical and locally available, their nutrient composition and digestibility are unreliable because they have variable nutrient composition and are lowly digested, which harms the performance of the animals. In an intensive livestock system, the feed is 60-70 percent of the total cost of production (Guo, et al. 2019). Moreover, ineffective use of nutrients also causes nitrogen and phosphorus losses, greenhouse gas emissions, eutrophication and water pollution.

To reduce these, nutritionists seek alternative sources of feed, feed formulation and feeding methods to enhance the efficiency of nutrients, cost reduction, and environmental effects. Sustainable livestock production is identified as the comprehensive model that incorporates productivity, economic effectiveness, environmental sustainability and animal welfare. Resource-efficient feeding systems aim to enhance nutrient use and decrease nutrient loss without affecting growth performance and the product qualities (Guo, et al. 2019). New technologies and methods, such as precision nutrition, computational feed formulation and the use of

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alternative feed ingredients like insect meal, algae and single-cell protein, have a good potential for sustainable production (Downs et al., 2022; Tomberlin et al., 2023). Also, livestock production can be improved with nutrient digestibility, gut health, and immune functioning by the use of functional feed additives, including enzymes, probiotics, prebiotics and phytogenic compounds (Windisch et al., 2008). This chapter reviews recent advances in nutrition and feed formulation strategies that enhance the sustainability of livestock production. It emphasizes scientific and technological innovations that improve nutrient utilization efficiency, reduce production costs, and mitigate environmental impacts.

FUNDAMENTALS OF LIVESTOCK NUTRITION

The nutrients are necessary to sustain the physiological processes that are vital in the body, such as respiration, circulation, transport of nutrients and wastes, thermal regulation, digestion, neural activity and muscle activities. There is a continuous turnover in body tissues and cellular components, with degradation and synthesis taking place at the same time to ensure that physiological integrity and functionality are preserved. Indicatively, the liver cells are 4-5 days old and the half-life of the hepatic cells is 4-5 days, i.e., half of the liver cells are replaced in this duration. Enzymes have shorter turnover rates still, e.g., ornithine decarboxylase has a turnover rate of 10 -30 minutes and Acetyl-CoA carboxylase has a turnover rate of approximately 48 hours. In order to maintain such active regeneration processes, the animals need a constant supply of multiple nutrients, such as energy, water and specialized biomolecules needed to build up the tissues as well as deal with the metabolic waste produced during the process of degradation. The use of forage in ruminants depends on the fermentation of microbes; knowledge of rumen digestion is a basis for coming up with biotechnological advancements in ruminant diets. The rumen is one of the structures of the bovine digestive system and it acts as an anaerobic fermentation chamber that helps to maintain a rich and diverse microbial community. In these microorganisms, the feed fed on is fermented to produce volatile fatty acids (VFAs) and methane and carbon dioxide as sources of primary energy to both microorganisms and the host animal (Cholewińska et al., 2020).

The composition of the ruminal microbiota is dynamic and closely influenced by diet. The degraders of fibrous and non-fibrous carbohydrates, as well as proteins, in ruminants are anaerobic bacteria, protozoa and fungi. Poultry converts feed into food products quickly, efficiently, and with relatively low environmental impact relative to other livestock. Their high rate of productivity results in relatively high nutrient needs. Poultry require at least 38 nutrients in their diets in appropriate concentrations and balance. Feeding standards for pigs are typically categorized according to physiological stage and body weight. Nutritional requirements differ between suckling pigs, weaners, growers, and finishers. Suckling pigs primarily depend on the sow's milk for nourishment, but should receive creep feed to facilitate the transition to solid diets. Weaners, generally weighing between 7.5 and 30 kg, have been separated from the sow and require nutritionally dense diets to support rapid growth and digestive adaptation (Blavi et al., 2021). Nutrients are divided into two main categories. One is the macronutrients, comprising most of the body of the animal, such as carbohydrates, proteins, lipids, and water. The second one is micronutrients, including minerals, vitamins, and exogenous enzymes.

Carbohydrates constitute a significant category of organic substances, which are composed of carbon, hydrogen, and oxygen, and in most cases, have a 2:1 ratio of hydrogen and oxygen, such as water. The name carbohydrate is derived from the French term hydrate de carbone, which translates to carbon mixed with water. These are both simple and complex compounds (sugars and starch and cellulose), respectively. Other elements or functional groups are also found in some carbohydrates and are referred to as derived carbohydrates. Carbohydrates do not provide blood glucose, which is essential to the physiological functions. Without them, glucose can be synthesized in the presence of fats and proteins in a process which is referred to as gluconeogenesis and is dominant in carnivorous animals like felines and canines. Later in 1838, a collection of organic compounds was identified and described by the Dutch chemist G.J. Mulder, following which he considered these to be the fundamental structural and functional units of all living tissues. These substances, which were subsequently to be known as proteins, were identified as essential factors in the life process, the main foundation of growth, support and productivity in animals. Lipids are an amorphous group of hydrophobic biomolecules predominantly made up of triacylglycerols, fatty acid derivatives and other fat-soluble substances. They are also described as soluble in nonpolar organic solvents like ether, chloroform and hexane and insoluble in aqueous media. Lipids are part of cellular structures in both plant and animal systems, and are critical controlling factors in metabolic regulation and energy homeostasis. Triacylglycerol is the major lipid fraction, which constitutes more than 90 percent of the total lipid reserves (Saha and Pathak, 2021).

The Asian region had contributed to world meat production by about 18 percent in 1975, and far greater amounts of 42 percent in 2010. On the same note, its contribution to the world milk production increased by 12.7 percent to 35.9 percent during the same time. Yet, the per capita consumption of foods of animal origin in Asia is still lower than the global average, with meat consumption being estimated to be approximately a quarter and milk consumption being approximately four times less. The adequate nutrition of livestock is a factor that is very important in terms of its productivity. Developing rations offering the best mixture of important nutrients, based on the physiological condition of the animal as well as its production capacity, is the key to sustained performance, enhanced feed efficiency, and the sustainability of the entire production process. One of the greatest problems facing livestock production systems is the lack of consistency in the availability of the feed resources, as well as their nutritional value. The availability of arable land is restricted by seasonal changes, and the lack of food to feed people competes with human food in most areas, leading to a lack of food (Kumar et al., 2025).

The other issue that is of the greatest concern in livestock production and formulation of feeds is feed stuff quality and anti-nutritional factors. ANFs are naturally occurring or artificial substances that are found in animal diets in amounts that may cause interference with the digestion, absorption, or metabolism of nutrients and eventually have an impact on the health and growth of the animals and their overall productivity (Abu Hafsa et al., 2022). Most recent studies have investigated the physiological impacts of antinutritional factors (ANFs) on various biological systems, where the compounds are found to have both positive and negative effects. The impacts are usually decreased intake and intake of feed, making up complexes with dietary proteins and essential nutrients that may not only interfere with their bioavailability but also, in extreme situations, result in toxicity or death. On the other hand, some ANFs are also reported to have desirable characteristics, including the reduction of parasite burden, a reduction in ruminal protein breakdown, and alleviation of methane emissions and bloating of ruminants. Since these compounds have the potential to affect animal health and production, livestock producers ought to know what these compounds are and put proper management plans in place to ensure that their adverse effects are minimal, while utilizing their potential positive effects. There is an accepted fact that nutritional imbalances have a significant impact on the health, productivity, and general performance of farm animals. Field studies have consistently identified both deficiencies and surpluses of dietary protein and energy, particularly within smallholder and informal production systems, where feed formulation and nutrient supply are often inadequately managed. However, dietary imbalance remains one of the major constraints to livestock productivity in many developing countries (Singh et al., 2024).

LIMITATIONS OF CONVENTIONAL FEED RESOURCES

The livestock production directly depends on the quality, quantity and continuous supply of feed resources to producers. Conventional feed resources such as cereal grains, oilseed cakes, roughages and forages form the foundation of most livestock diets across intensive, semi-intensive and small household systems. However, growing demographic pressure, climate variability and the expanding global demand for animal-source food have collectively strained the feed supply chain, which indicates the structural weaknesses of conventional feed resource systems. The limitations of these conventional feed resources (Table 1) are directly linked to economic or nutritional dimensions, environmental, ethical, and food security concerns and this is alarming situation for the long-term viability of current feeding practices. Globally, livestock consume one-third of all cereal grains, including maize, barley, wheat, sorghum and millet etc. (Mottet et al., 2017). These cereals are human edible, dependency of livestock on these cereals directly intensifies competition between food and feed sectors, especially in undernutrition regions such as in South Asia and sub-Saharan Africa. Diverting substantial portions of cereal crops to livestock feeding undermines food security and escalates feed costs in these regions. Furthermore, the nutritional profile of grains is mainly rich in starch (carbohydrates) but deficient in structural fiber, essential amino acids such as lysine and methionine and minerals, which is not ideal for ruminant nutrition. Excessive inclusion of cereal grains disrupts the ruminal ecosystem by altering ruminal Ph, which leads animals to metabolic disorders such as subacute ruminal acidosis (SARA), laminitis and reduced fiber degradation efficiency (Owens et al., 1998). These metabolic disorders not only compromise productivity but also reduce the longevity and reproductive performance of high-producing animals. Hence, it is a need of hours to minimize the inclusion of human-edible grains in livestock rations and promotes human non-edible or low-cost biomass resources such as crop residues, agro-industrial by-products and aquatic plants.

Feed resource availability is also subject to pronounced seasonal and regional fluctuations. In tropical and subtropical environments, feed supply closely relates to rainfall distribution and cropping cycles which result in alternating periods of feed abundance and scarcity. During dry or lean seasons, green fodder production reduces up to 40-60%, and the crude protein content of available forages frequently falls below 6%, which is insufficient even for maintenance requirements in cattle and small ruminants (Kumar et al., 2022). In such circumstances, livestock farmers often resort to feeding cereal straws, maize stover, and paddy straw, which are abundant but nutritionally poor, with digestibility values as low as 40%. These feed stuffs contain low nitrogen and high indigestible portions such as lignin and silica. These sections inhibit the activity of microbes in the rumen and eventually disrupting the feed consumption. There is also the inability to store excess fodder by silage or haymaking, and a lack of efficient storage facilities, which also contributes to deficits in seasons. In result animals experience malnourished for a longer period which leads to weight loss, long calving intervals, low milk yield and suppressed immune competence.

The nutritional imbalances and the widespread occurrence of anti-nutritional factors (ANFs) in feed ingredients is also a major problem in conventional feeding systems. The nutrient composition of conventional feed is influenced by soil fertility, climate, crop variety and post-harvest handling. Crop residues such as wheat straw, rice husk and maize stover contain less than 4% crude protein and high fiber fractions which are poorly fermentable in the rumen. At the same time feedstuffs such as cottonseed cake, ground-nut cake and rapeseed meal are nutrient-dense. They contain anti-nutritional factors (ANFs) like gossypol, tannins, phytates and trypsin inhibitors that interfere with protein digestion and mineral uptake (Abu Hafsa et al., 2022). These compounds have negative impact on palatability, compromised nutrient degradability, reproductive failure and multi organ dysfunction syndrome. Interestingly, controlled inclusion of some ANFs, such as condensed tannins have beneficial effects by reducing ruminal protein degradation, methane production and bloat incidence. However, the lack of systematic detoxification or processing technologies in developing livestock systems limits the safe utilization of such feeds, thereby perpetuating nutritional inefficiencies.

Beyond the physiological considerations conventional feed production also exacts an environmental burden. Feed production accounts for 45 % of the greenhouse-gas emissions tied to animal agriculture because cultivating cereals and

Table 1. Diagnostic overview of major constraints in conventional feed resources and strategic implications for sustainable livestock nutrition

Limitation Domain	Indicative Parameters or Examples	Functional Impact	Strategic or Research Implications	References
High reliance on human-edible cereals	>30% of global cereal output used for animal feed; overlap with human diet in Asia and Africa.	Feed-food competition, volatile feed prices, reduced food security.	Promote non-edible biomass use (crop residues, by-products); adopt circular feed systems.	Mottet et al., 2017
Seasonal and regional feed scarcity	40-60% decline in forage biomass during dry seasons; poor fodder conservation in rainfed zones.	Nutrient deficiency, loss of body weight, reduced reproductive efficiency.	Develop silage/haymaking capacity; improve drought-resilient forages and feed banks.	Kumar et al., 2025
Nutritional disequilibrium in feedstuffs	Crude protein <4% in cereal straws; variable mineral bioavailability; imbalance in lysine-methionine ratio.	Low feed conversion efficiency; poor milk composition; suppressed immunity.	Employ supplementation, mineral fortification, or rumen-protected nutrients.	Saha and Pathak, 2021; Singh et al., 2024
Presence of anti-nutritional compounds	Gossypol in cottonseed cake, tannins in legumes, phytates in oilseeds, trypsin inhibitors in soy.	Reduced digestibility, mineral chelation, oxidative stress, reproductive issues.	Research detoxification, fermentation, and enzyme-aided neutralization techniques.	Abu Hafsa et al., 2022
Environmental intensity of feed production	Feed production contributes 40-45% of livestock GHG emissions; 900-1,000 L of water per kg of maize grain.	Increased carbon and water footprints; soil and biodiversity loss.	Transition toward low-input feed crops, agro-ecological practices, and carbon accounting in feed formulation.	Yue et al. 2017

oilseeds demands fertilizer, pesticide and irrigation inputs (Yue et al., 2013). Raising feed grain croplands commonly fuels deforestation, worsens soils and decadres biodiversity. These systems emit nitrous oxide which is a strong greenhouse gas that is released by the synthetic fertilizer and the nutrient runoffs lead to eutrophication of water bodies. Pakistan is one of the water-starved nations whose water consumption efficiency is deplorable in that every kilogram of maize grain production used approximately 900 liters of water. Also, in smallholder and peri-urban areas, reliance on imported material feeds like soybean meal causes fluctuations in global markets. These are some of the environmental and economic issues that underscore the need to adopt more resource-efficient feeding mechanisms that feed the agricultural wastes, by-products as well as the locally available alternative feeding materials. Succinctly, the issues surrounding traditional feed resources are a complex problem that comprises of economic ineffectiveness, nutritional incompetence and ecological unsustainability. Reliance on cereal grains causes stress on natural resources and seasonal inadequacy of feeds that cause endless under-nutrition of livestock. The nature of nutritional deficiency and ANFs increases decreases the biological performance of feed intake and the environmental impact of standard feed manufacturing. To sustain livestock productivity, the global feed industry needs to move towards grain-based, input-intensive feeding systems to resource-efficient, ecologically adaptive, and nutritionally balanced feeding mechanisms.

To sum up, the issues connected to traditional feed resources are a complex phenomenon with the roots in the economic incompetence, the nutritional and environmental inadequacy. This reliance on cereal grains strains the available natural resources and the livestock undergoes cyclic undernourishment due to the lack of seasonal feed. The lack of nutrients as well as the occurrence of ANFs, diminishes the biological effectiveness of feed usage and the environmental impact of the conventional feed production. For maintenance of livestock productivity, the global feed industry must shift from grain-based, input-intensive systems to more resource-efficient, ecologically adaptive, and nutritionally balanced feeding approaches.

ALTERNATIVE AND NOVEL FEED RESOURCES

The use of alternative feed resources that are economically feasible, nutrient-dense and sustainable is essential for the future of livestock production. After recognizing the ecological and nutritional constraints of conventional feeds, attention has increasingly turned towards alternative and novel feed resources such as by-products, underused biomasses and innovative protein sources to close nutrient loops within agri-food systems. The transformation of agricultural and industrial deposits into enriched livestock nutrients is carried out by these alternative resources which minimize food- feed contest and elevate circular economy (Kumar et al., 2022).

Agro-industrial by-products are the most immediately accessible category of alternative feeds. Products such as oilseed cakes (cottonseed, sunflower, sesame, groundnut), molasses and fruit or vegetable pomace contain appreciable levels of carbohydrates, proteins and fermentable sugars. Their inclusion in rations supports rumen microbial growth and energy balance while lowering production costs. For example, banana peel and grape pomace can replace up to 30 % of concentrate mixtures for dairy cattle without adverse effects on yield or milk composition (Montusiewicz 2024). Molasses functions both as an energy source and as a binder in urea-molasses-multinutrient blocks (UMMB), providing a convenient method for synchronizing rumen nitrogen and energy release. Beyond nutritional utility, these by-products also address environmental concerns by reducing organic waste discharge from food-processing industries. Improving forage and pasture systems is equally critical to feed resource diversification. The well-managed pasturelands sustain ruminant nutrition and provide benefits to soil, such as carbon sequestration and biodiversity conservation. The hybrid fodder (Napier-bajra, sorghum-sudan), protein-rich legumes (berseem, lucerne, cowpea) and rotational or silvopastoral systems enhance productivity and also conserve land and water. The ensiling and hay making stabilize feed supply across seasons reduce the effects of drought and monsoon variability. In Pakistan, smallholders adopt maize and sorghum varieties for both grain and fodder, and this has increased annual green-fodder availability by nearly 20 %, demonstrating the benefits of practical forage innovation.

Microbes such as yeast, algae and bacteria derive insect-based meals and single-cell proteins (SCPs). Insect meals from black soldier fly larvae, housefly maggots and mealworms provide 40-60 % crude protein and amino-acid profiles comparable to fishmeal (Tomberlin et al., 2023). Insect meal production on organic waste substrates turns environmental waste into nutrient assets. Yeast and algal SCPs, i.e., *Saccharomyces cerevisiae*, *Spirulina platensis* and *Chlorella vulgaris* supply digestible protein, B-vitamins, pigments and polyunsaturated fatty acids. The media cultures like methane or ethanol effluents have the potential to grow a microbial community, which enables viable feed manufacture from industrial gases (Downs et al., 2022). Some studies have shown that these microbes have a significant impact on growth performance, immune response and nutrient digestibility with partial replacement of soybean meal in poultry and aquaculture species.

Some unconventional feed resources, such as duckweed (*Lemna minor*), azolla (*Azolla pinnata*) and water hyacinth (*Eichhornia crassipes*), show rapid growth and have a potential of 22-37% crude protein with balanced amino-acid profiles (Baek et al. 2021). *Duckweed* and *azolla* can be grown on small farm ponds by using nutrient-rich wastewater. *Moringa oleifera* leaves and *Leucaena leucocephala* foliage are also used as valuable protein supplement sources with antioxidant properties, but in this case, inclusion levels must be moderated to avoid adverse effects or toxicity. Different processing methods, such as shade-drying, chopping, and limited fermentation, improve palatability and reduce anti-nutritional factors, making these resources practically available for village-level feeding systems. For the adoption of any novel feed ingredient, nutritional evaluation and safety assurance are the most important parameters. Lab analysis, such as chemical analyses, in vitro gas production and in vivo digestibility trials, provides essential data on metabolizable energy, amino-acid balance and fiber fractions (Guo et al., 2019). Quality check protocols must also be screened for mycotoxins, heavy metals and pathogenic microbes. Equally important are life-cycle assessments (LCA) that quantify the environmental footprint of these feeds, ensuring that sustainability claims are evidence-based rather than assumed.

In resource-limited settings such as Pakistan, India and Nepal, these innovative feed options can be applied using straightforward on-farm methods. Sun-dry fruit and vegetable residues are mixed into concentrate rations, small cooperative units can manufacture urea-molasses blocks using locally available molasses and oilseed cake, and duckweed or azolla ponds established on wastewater channels can provide daily protein supplements at minimal cost. Simple insect-rearing units for black soldier fly larvae can be installed near livestock sheds, converting manure and household waste into protein-rich feed within ten days. The residual frass from these larvae serves as an organic fertilizer, closing nutrient cycles. When integrated into mixed crop livestock systems, such practices reduce feed expenditure by 20-30 %, improve nutrient recycling and lower waste disposal problems, illustrating that sustainability can be achieved through locally adaptable, low-cost innovations rather than high-technology inputs.

ADVANCES IN FEED FORMULATION STRATEGIES

The sustainability of livestock is reliant on the presence of feed materials and the accurate development of feeds that satisfy the nutrient needs of livestock. The current formulation of feed is based on scientific principles, where the bioavailability of nutrients and species-specific reactions are included in the diet. By utilizing the concept of precision nutrition, the livestock industry will be in a position to improve production, decrease the cost of feeding and decrease the wastage of nutrients. Precision nutrition can be considered as a rationing of nutrients based on physiological requirements as opposed to feeding a ration to the whole animal population. In this method, fixed nutrition tables are omitted and instead, there is a systematic method of connecting nutrient supply to body weight increase, composition of feeds, reproductive performance and environmental factors. Predictive frameworks, such as Cornell Net Carbohydrate and Protein System (CNCPS), National Research Council (NRC) nutrient models, and the INRA feed unit system, measure rumen dynamics, post-ruminal digestion and tissue nutrient partition. These formulation models help nutritionists identify a balance between rumen-degradable and undegradable protein, volatile fatty acid (VFA) yield, and energy to protein ratios to increase the effectiveness of feed conversion (Hanigan et al., 2021).

The other pillar of the advanced formulation strategies is economic optimization. The least cost formulation (LCF) model utilizes linear programming to compute the most economical blend of feed substances to match the desired nutrient makeup. Some programs like Brill, FeedSoft, MixitWin and WinFeed are used to apply mathematical steps in order to reduce costs and at the same time guarantee the biological needs of animals are addressed. Such programs can analyze data describing the composition of nutrients of ingredients, even non-tradable, e.g., fruit pomace or insect meal, and give possible substitutions, which preserve the balance of the diet. When done properly, total feed expenditure can be reduced by 10-25 and animal performance increased (Saha and Pathak, 2021). One of the strategies that can be employed to enhance the efficiency of nutrient utilization in contemporary livestock production systems is phase feeding. Nutrient levels are regulated in this system based on age, weight and physiological need instead of providing a single ration in the production cycle. The amounts of energy and protein are gradually reduced at the starter, grower, and finisher stages, accompanied by aiding growth performance and nutrient digestibility in broiler chickens (Azevedo et al. 2021). Similarly, phased feeding increases optimum lean tissue deposition and yield of milk components, inhibits mismanagement of nutrient and minimizes environmental loading in pigs and in dairy cattle. On-farm monitoring equipment, such as simple feeding and yield measuring equipment have helped in making amends in time to ensure that nutrient delivery is made according to the physiological condition of the animal. Precision feeding has another dimension with species-specific formulation. The objective of ruminant diets is to maximize rumen fermentation and microbial production through the degradable fiber, starch, and protein fractions, whereas the poultry and swine feeds focus on digestible amino acid profiles and energy distribution. Carbohydrates to effective fiber ratio in dairy cattle directly affects milk fat production and pH maintenance in the rumen, but in the small ruminant, the supplementation of the bypass protein and mineral contents has a crucial role in reproductive performance and wool development. Additions of feed supplements like probiotics, enzymes, and organic acids further optimize nutrient absorption, intestinal health, immune stability, and nutritional accuracy is in line with physiological health (Windisch et al., 2008). What has been refined now is the formulation of feed to the level of nutrient bioavailability and digestibility, since it has been discovered that the level of total nutrient concentration may not be the best measure of the efficiency of utilization. Nutritionists can determine the digestible nutrient fractions instead of the total nutrient fractions with laboratory techniques, including in vitro and in-situ degradability testing and ileal digestibility testing. The inclusion of these coefficients in formulation matrices enhances the precision of the metabolizable energy, supply of amino acids, and phosphorus availability (Guo et al. 2019). Also, the use of enzyme-corrected nutrient matrices in the diet of poultry and swine has the benefit of ensuring that the contribution of exogenous enzymes (xylanase, phytase and protease) is reflected accordingly, thus avoiding nutrient overestimation and reducing unnecessary nitrogen and phosphorus release to the environment. Using bioavailability data will provide added strength to ration formulation as a predictive system that frames the relationship between food chemistry and biological performance to optimize the performance of animals and ecological sustainability (Table 2).

The evolution of feed formulation has transformed livestock nutrition from a static process into a responsive system that balances biological precision, economic optimization, and environmental stewardship. The integration of predictive nutrient models, least-cost algorithms, and digestibility databases ensures that every gram of feed contributes efficiently to animal productivity. Practical tools and improved management practices are allowing these advanced formulation approaches to be adopted by small-scale farmers, thereby extending access to precision nutrition. Collectively, these developments form the scientific and technological foundation of sustainable livestock feeding and establish the framework for incorporating functional feed additives and nutrigenomic insights into the next generation of animal nutrition strategies.

FEED ADDITIVES AND FUNCTIONAL INGREDIENTS

The development of animal nutrition science has enhanced more than the classical goal of providing nutrients to maintain and produce. The modern-day feeding methods are currently focusing on the utilization of functional ingredients that have been shown to maximize digestion, immunity, and metabolism and minimize the use of antibiotic growth promoters. These supplements affect physiological functions and microbial ecology of the host and boost performance and quality of products. Functional nutrition concept combines the use of microbiological, biochemical and technological methods to enhance gut integrity, nutrient use and system resilience that underlie livestock health, productivity and welfare. The introduction of probiotics, prebiotics and symbiotics as natural products to control the intestinal microbiota has been a significant change in this area. The beneficial microbial species, such as Lactobacillus, Bifidobacterium, Enterococcus, and Saccharomyces, act as probiotics capable of inducing gut homeostasis by competitive exclusion of pathogenic species, antimicrobial compounds secretion, and regulation of mucosal immunity. These probiotics improve the digestion of fiber, the amount of food eaten, and the proportion of food to energy eaten in ruminants and poultry, decreasing enteric diseases, including *salmonellosis* and *colibacillosis* (Markowiak and Śliżewska, 2018). Prebiotics such as mannan-oligosaccharides (MOS), inulin and fructo-oligosaccharides (FOS) are fermentable compounds that selectively enhance the proliferation of the desirable microbes within the gastrointestinal tract. Probiotics and prebiotics have a synergistic effect with each other to maintain the balance of microbes, maximize the nutrient intake, and stabilize the gut during thermal or dietary stress.

Precision feeding systems contain enzymes and organic acids. Exogenous enzymes (cellulase, xylanase, b-glucanase, phytase, and protease) are being very popularly employed to increase the digestibility of feed materials, especially those with high levels of non-starch polysaccharides or phytate-bound phosphorus. Fibrolytic enzymes increase rumen fermentation and volatile fatty acid generation in ruminants, and decrease the viscosity and release of encapsulated nutrients in the digesta in poultry, increasing the metabolizable energy and amino acid availability. Phytase supplementation in poultry and swine food feed not only enhances the phosphorus absorption by 25-35 percent, but also decreases phosphorus release and contamination to the environment (Ravindran et al. 2016). In the same manner, organic acids, like formic, lactic, citric and butyric acid, reduce the pH in the gut, prevent the growth of pathogenic bacteria and stimulate the secretion of digestive enzymes. Organic acids have been found to improve villus height, nutrient absorption and are a useful alternative to antibiotic growth promoters in piglets and broilers. The synergistic interaction of both enzymes and organic acids often shows complementary effects, enhancing the release of nutrients, the state of intestinal and overall performance at the same time.

Phytogenic feed additives (PFAs), plant-based bioactive compounds such as herbs, spices, and essential oils, have recently become a popular topic of discussion as multidimensional feed enhancers. Essential oils, flavonoids and phenolics in extracts of oregano (*Origanum vulgare*), garlic (*Allium sativum*), turmeric (*Curcuma longa*), cinnamon (*Cinnamomum zeylanicum*), and neem (*Azadirachta indica*) have potent antimicrobial, antioxidant and digestive stimulant effects (Windisch et al., 2008). These compounds alter the rumen microbial population, increase salivary secretion and

Table 2. Advanced feed formulation strategies and their functional advantages in sustainable livestock systems

Formulation Strategy	Scientific Basis	Functional Advantages	Practical Examples / Applications	Indicative Impact	Reference
Precision nutrition modeling	Real-time estimation of nutrient demand using physiological and production data	Matches feed supply to exact animal requirements; improves nutrient efficiency	NRC, CNCPS, INRA models; digital ration-balancing tools	5–10% higher feed conversion efficiency	González et al., 2018
Least-cost formulation (LCF)	Linear programming optimization of ingredients based on cost & nutrient value	Minimizes ration cost while maintaining nutrient balance	WinFeed, Brill, FeedSoft, MixitWin	10–25% reduction in feed cost	Smith et al., 2020
Dynamic / phase feeding	Adjusting nutrient density according to growth or lactation phase	Improves nitrogen retention; reduces nutrient waste	Broiler starter–grower–finisher programs; dairy lactation-curve feeding	15–20% lower nitrogen excretion	Pagliari et al., 2020
Species- & stage-specific diets	Tailoring macro- and micronutrients to species physiology & stage of production	Improves health, reproduction, and product quality	Ruminant fiber–starch balance; poultry amino-acid optimization	10–15% gain in productivity	Pagliari et al., 2020
Integration of bioavailability data	Use of digestible nutrient coefficients; enzyme-corrected nutrient matrices	Enhances formulation precision; reduces environmental nutrient loading	In vitro digestibility assays; enzyme matrices; LCA-based formulation	20–30% better nutrient utilization	Zhang et al., 2022
Digital and automated formulation tools	AI-, cloud-, smartphone-based computation platforms	Improves accessibility and decision-making consistency	Mobile ration apps; cooperative feed-mill software	Improved feed accuracy & reliability	Zhang et al., 2022

enzyme activity that increases the efficiency of nutrient utilization. PFAs enhance carotenoid pigments in natural carotenoids in poultry by increasing feed intake, carcass yield, and the yolk color. They can mitigate the emission of methane in ruminants by modulating the methanogenic activity as well as enhancing the production of propionate. Another important factor that explains the rising popularity of phytogenics is that they are consumed as a natural or natural-friendly feed additive, which seems to be in line with the rising popularization of animal products with zero antibiotics and zero residue. To keep animals healthy and perform effectively, especially when the animals are subjected to severe stress, both antioxidants and immunomodulatory supplements have become standard practice. Oxidative stress disrupts cellular activities, reproductive activity and immune efficacy; thus, incorporation of antioxidants like vitamin E, selenium, polyphenols and plant flavonoids is important to counteract oxidative stress. When administered in their optimal ratios, vitamin E and selenium enhance membrane integrity and antibody levels, whereas natural polyphenols of grape seed, green tea and rosemary show good free radical scavenging capacity.

Nucleotides and seaweed polysaccharides (Immunomodulators) are known to stimulate adaptive and innate immune responses and help animals to fight infectious diseases, as well as metabolic diseases. They are especially useful in intensive production systems where the load of stress and pathogens is greater. Their use in combination positively affects productivity characteristics and positively affects the product characteristics in terms of milk oxidative stability, meat color and shelf life. One of the more rapidly emerging areas of feed additive research is the use of nanotechnology, which promises novel delivery modes and efficiency enhancement of bioactive compounds. In nanoparticle systems like nano-selenium, nano-zinc oxide and nano-silica, the surface area and bioavailability are increased, and thus the inclusion rates are lower with better biological effects. The nano-carriers containing essential oils, vitamins and probiotics ensure the protection of these substances against the degraded state in the process of feed processing and digestion, and the output of these substances is directed in the gastrointestinal tract. Nano-encapsulated curcumin or garlic oil is also being used as an example, where the nano-encapsulation method has been proven to be more effective in antimicrobial action and antioxidant capacity than the conventional counterparts (Linh et al. 2022).

On the same note, nano-mineral supplementation improves the activity of enzymatic cofactors, immune systems and reproductive performance in cattle and poultry. Nevertheless, it is essential to carry out safety testing and harmonization of nanoparticle dosage to avoid tissue deposition and environmental hazards. With more research, nanotechnology will aid in the revolution of designing additives in the feeds by providing precise delivery, stability, and reduced impact on the environment. A combination of these functional ingredients is an interdisciplinary method of animal feeding so that nutrition is not only used to support growth, but also to regulate health, microbiota, and metabolism. Practically, the choice of feed additives ought to reflect on the production goals and objectives, species-specific digestive physiology, feed composition and cost-effectiveness. The field trials have shown that the substitution of antibiotic growth promoters with probiotics, enzymes, or PFAs can maintain or even increase the feed ratio and the growth rate without affecting animal welfare. The synergistic effect of fiberlytic enzymes and essential oils in ruminants improves fiber degradation and rumen fermentation activity and in poultry, probiotics in combination with organic acids stabilize pH and microbial diversity of the gut. Finally, the additive-based nutrition interventions allow the producers to obtain high performance with low levels of inputs, which is consistent with the world objectives of sustainable, safe and ethical animal production.

NUTRIGENOMICS AND PRECISION LIVESTOCK FEEDING

Molecular biology applied to animal nutrition has led to a new field of nutrigenomics, the study of the relationship between nutrients and gene expression and genetic variation and nutrient utilization. This interface region is the transition between formulation of feeds and functional genomics and is intended to realize nutrition not as a provider of nutritional good but as a regulatory stimulus able to change cellular activities, metabolic routes and phenotypic expression. Nutrigenomics insists on the fact that animal reactions to a diet are pre-determined by the genetic background and vice versa; nutrients may serve as environmental signals, modulating gene transcription, protein synthesis, and the formation of metabolites. Simultaneously, nutrigenetics is concerned with genetic polymorphisms that determine the rate at which different animals metabolize, absorb and react to nutrients. At the same time, these sciences open the door to the age of precision feeding, when rations are not only species specific or specific to the stage of production but also may be genotype specific to the animal.

Nutrient-gene interactions at the molecular level occur via complex biochemical signaling networks. The interaction of nutrients and their metabolites with the transcription factors, enzymes and receptors regulates the gene expression in metabolic pathways. Indicatively, nutrients that regulate energy conditions exert their effects on the activation of AMP-activated protein kinase (AMPK) and mTOR pathways that control the energy status, cell growth and protein synthesis. Equally, dietary fatty acids are known to regulate the peroxisome proliferator-activated receptors (PPARs) and sterol regulatory element-binding proteins (SREBPs), which are lipid metabolic and adipogenic regulators. Methionine and leucine are amino acids that regulate the epigenetic processes of DNA methylation and histone acetylation that control the rate of gene transcription and cellular differentiation (Sun et al., 2023).

Ruminal access to rumen-protected methionine and choline has the potential to change the hepatic gene expression of lipid transport and antioxidant defense in ruminants, leading to the subsequent improvement of liver health and milk composition during the periods of transition. The increased application of high-throughput technologies, including transcriptomics, proteomics, metabolomics and metagenomics, has shown complicated nutrient gene interactions to set up characteristics, including feed efficiency, immune resilience, reproductive performance and product quality. Based on these molecular revelations, precision livestock feeding (PLF) is a notion that involves the use of sophisticated monitoring systems to administer nutrients on a dynamically changing basis based on the actual requirements of the animal. Sensors, automated feeders, imaging devices and wearable technologies control precision feeding systems to constantly monitor feed intake, weight gain, rumen activity, and physiological measurements such as temperature and behavior. Machine learning algorithms and nutrient response models process the data and automatically make positive changes to the feed composition, quantity and timing. Dairy systems with automated milking and feeding robots can determine the output of each cow, the health of the body and rumination to feed the individuals more efficiently, both to reduce wastage of feed and nutrition imbalances. Optical sensors and smart scales installed in precision feeding units determine the growth pattern of poultry and regulate the food consumed in order to achieve even body weights and a high feed ratio. These data systems are indicative of the principle of feeding the animal, not the group, where the animal is fed in amounts precisely in relation to physiological need. Data integration and a decision-support system that can translate complex information into a practical feeding strategy are essential to the success of precision livestock feeding. Complex nutrient modeling systems, including the Cornell Net Carbohydrate and Protein System (CNCPS) or NRC nutrient models, are being interfaced with on-farm data streams to model nutrient flows and estimate performance outcomes under different diet conditions. These systems are improved through artificial intelligence (AI) and predictive analytics, which constantly learn using farm-level data to optimize the formulation of the ration and identify the initial symptoms of nutrition-related disorders. Nutritionists can now see trends in feed efficacy, methane production and nutrient excretion in real time in digital dashboards. Also, the shared data through the clouds between feed mills, veterinarians and farm managers brings uniformity in feed formulation and traceability, which optimizes biosecurity and product safety. Internet of Things (IoT) devices and analytics enable the population to rely on cyber-physical systems to optimize the processes of livestock feeding and monitor their sustainability in the context of optimization and real-time monitoring (Tangorra et al., 2020).

The intersection of nutrigenomics and precision feeding is a paradigm shift in animal nutritional management, having the population-based feeding approach shifted to a more individualized feeding management approach. Identified molecular biomarkers based on nutrigenomic research can be used alongside predictive models to determine nutrient efficiency, health status, or reproductive feasibility, and hence, ration design based on genotypes is possible. As an illustration, the expression of the hepatic genes of *DGAT1* and *SCD1* has been associated with the synthesis of milk fat in dairy cattle, whereas *LEP* and *MC4R* gene polymorphisms have been associated with feed efficiency in beef cattle and swine. When these genetic markers and accurate feeding systems are implemented, there is an opportunity to conduct certain nutritional interventions that will help to increase the production qualities without necessarily consuming too many resources. This principle indicates the concept of sustainability in nutrition that is biologically particular, where all the nutrients are eaten to their full potential, and the leftovers are minimized through the use of informed and evidence-based feeding behavior. Nutrigenomics-based feeding regimes are still very young and they hold massive potential in the future. The use of genomic and metabolomic profiling has already been applied in research herds in order to analyze high-performing animals and optimize the nutrient delivery at the most sensitive point in the lactation or growth stage. Portable biosensors, which are capable of monitoring the presence of other metabolites like 2-hydroxybutyrate in milk and urea in blood in real time, can be used to measure the metabolic status and, therefore, manipulate the ratio in time. Precision technologies to feed these ruminants, whether through automated feed bunks or robotic milking parlors, or smart poultry feeders, are being adopted by the developed ruminant industries and are trickling into the progressive farms in the developing world. As more data analytics and IoT connection and genomic characterization are developed, the combination of nutrigenomics and precision livestock feeding can reinvent the future of animal nutrition as a biological and technological science (de Las Hazas et al., 2022).

ENVIRONMENTAL SUSTAINABILITY IN FEED PRODUCTION

Another key factor in determining livestock sustainability systems is the environmental footprint of the feed production, which makes feed the highest cost and the major source of greenhouse gas emissions in animal agriculture. As the world continues to grow in terms of animal products, it is urgent that feeds that are nutritionally optimized as well as socially responsible are produced. The life cycle assessment (LCA) offers an extensive structure to assess the effects of cultivation, processing of feed ingredients, transportation, and on-farm use, and quantifies carbon emissions, energy usage, water use and land use. These types of analyses allow identifying high-impact feed ingredients, such as imported soybean meal, that can cause significant effects on the environment (deforestation and transport-related emissions), whereas legumes grown locally and agro-industrial by-products can have a tremendous positive impact. In addition to choosing ingredients, the feed formulation plans have the potential to directly reduce the emission of methane and nitrogen by ruminants. Enteric fermentation can be controlled to reduce the production of methane and reduce the excretion of nitrogen, which results in the loss of nutrients to the environment by increasing digestibility, energy protein ratios, inclusion of natural feed supplements like tannins, saponins, essential oils and probiotics. These methods are further complemented by precision feeding, which provides nutrients that are needed by the individual animal based on their physiological needs so as to prevent overfeeding and the wastage as well as pollution of the environment (Herrero et al., 2013).

Besides mitigation of emissions, the concept of the circular economy is also being implemented to nourish production, with an accent on the reuse of agricultural and industrial by-products. The residues of the food industry (brewery grains, fruit pulp and oilseed cakes), or crop residues (straw and husks) can be used to make high-value feed components. The development of new technologies like microbial fermentation and insect-derived protein streams turns organic waste streams into the feed that can sustain nutrition, which decreases the usage of traditional crops and decreases the total ecological imprint. Resource-use efficiency is another crucial aspect, as water and land are limited and stretched to the limit. This is achieved by the use of drought-tolerant, high-yielding crops, precision irrigation and soil conservation practices, as well as an integrated agroecological system (e.g., multi-cropping or silvopastoral system) in order to maximize the yield per unit of water and the yield per unit of land and ecosystem services are never lost. All these strategies, life cycle informed choice of ingredients, enteric and manure emission reduction, circular use of feed, and efficient utilization of water and land in making feed can convert a resource-intensive system into a climate-sensitive system. They reduce environmental influences, besides enhancing productivity and economic feasibility, complementing advances in precision livestock nutrition and nutrigenomics, and resulting in a smart future of animal nutrition that is environmentally accountable, these integrative approaches (Toplicean and Datcu, 2024).

ECONOMIC AND POLICY PERSPECTIVES IN SUSTAINABLE FEED PRODUCTION

There are economic benefits and environmental benefits to sustainable feed innovations; however, the cost analysis and policy frameworks are necessary to accomplish the innovations. The cost analysis is important to define whether the strategy of sustainable feeding, with its precision feeding taking into account the by-products of agro-industrial products and the use of feeding additives which minimize the impact of the methane and nitrogen emissions, is economical. The analyses consider such inputs as labor, investment in infrastructure, gains and decrease of purchases due to environmental compliance penalties, which would allow the stakeholders to identify the strategies that will not only be environmentally friendly, but also at a cost that is affordable. Government policies are very important when it comes to making decisions aimed at adopting sustainable feeding practices. The regulatory systems that enhance the consumption of low-impact feed materials, place restrictions on GHG emissions, or require producers to include nutrient management strategies push producers to incorporate environmentally responsible activities in their production (Herrero et al., 2020).

Moreover, subsidies related to precision feeding equipment, tax breaks on using recycled feeds or alternative feeds and grants to develop green feed technologies speed up innovation adoption, eliminating the initial high financial costs of farmers and feed producers. The process of commercializing sustainable feeds is found in the market dynamics where the consumer demand for environmentally responsible animal products grows, providing the value-added products and niche markets. There are, however, challenges to avoid mass adoption, including the high cost of initial investments, fluctuating availability of other feed resources, and a lack of awareness of those who are producers themselves. With economic review, policy incentive and market system, the livestock industry can shift to a sustainable and profitable feeding framework, in which environmental responsibility is accompanied by financial profit and novel feed technology is successfully applied to mass production (Makkar, 2016).

FUTURE TRENDS AND RESEARCH DIRECTIONS

The future of feed production and livestock nutrition is becoming more and more advanced due to technologies, molecular innovations, and climate-smart strategies. Dynamic modification of the feed delivery depending on the physiological state of every animal, their behavior, and state of production will be possible through the use of smart farming systems such as precision sensors, automated feeders, wearable devices and real-time monitoring platforms. This helps in the optimization of nutrients and minimization of waste and environmental pollution. Meanwhile, artificial intelligence (AI) and machine learning are not only transforming feed formulation by estimating nutrient requirements, simulating metabolic reactions and finding the optimal combinations of feed ingredients. Genome-edited crops have immense potential on the molecular level, as they are superior in nutrition, featuring higher protein content and better amino acid profiles and greater micronutrients. The developments have the potential to minimize the reliance on conventional feed sources and minimize the ecological stresses associated with feed production. Food systems that are resistant to climate are beginning to be developed as well, such as drought-resistant forages, heat-tolerant varieties of crops with adaptive storage and processing procedures of feed, and adaptive feed storage and usage. These inventions are geared towards maintaining a consistent quality of feed and supply due to the fluctuating environmental factors. In spite of such developments, there are still gaps in the research, including how nutrient genes interact with microbiomes, developing AI algorithms applicable across different production systems and how to scale up innovative feed technologies at an economical scale. The solution to these needs would involve the efforts of nutritionists, geneticists, agronomists, engineers, data scientists and policymakers to come up with combined solutions that enhance productivity, sustainability and livestock systems resistant to future challenges.

CONCLUSION

This chapter describes the process of modulating livestock production through the incorporation of alternative feed resources, precision diet planning and functional feed additives. A threatening scenario will increase the cost, nutrition and environmental impact, should we continue relying on the traditional grain-based feed resources. The strain on the resources may be reduced through the use of alternative materials and this includes agro-industrial by-products, aquatic plants, single-cell proteins and insect meals. Manufacturers will be able to optimize their use of nutrients and take solutions that are more relevant to farm realities. Some of the models that maximize animal health and livestock production based on economic and environmental goals include precision nutrition models, least-cost diet formulation and phase feeding. Innovations in bioavailability modeling, digital formulation tools and functional additives are some of the new opportunities to improve animal welfare, productivity, and sustainability. These enhancements are shifting from the stagnation-oriented, input-based systems to the dynamic, data-driven models, founded on environmental stewardship. Introduction is made in a practical dimension on economic feasibility, the involvement of the farmers and friendly policy. Knowledge gaps and the development of innovations into sustainable agricultural processes need more research and interdisciplinary collaboration. Not only is it probable that the transition to sustainable livestock nutrition will increase productivity and profit, but also food security, environmental conservation and rural livelihoods.

REFERENCES

Abu Hafsa SH, AA Hassan, MM Elghandour et al., 2022. Dietary anti-nutritional factors and their roles in livestock nutrition. Sustainable Agriculture Reviews 57: Animal Biotechnology for Livestock Production 2, Springer International Publishing, Cham, pp:131–74.

Azevedo JM, MP Reis, RM Gous et al., 2021. Response of broilers to dietary balanced protein. 1. Feed intake and growth. Animal Production Science 61:1425–34.

Baek G, M Saeed, HK Choi, 2021. Duckweeds: their utilization, metabolites and cultivation. Applied Biological Chemistry 64:73.

Blavi L, D Solà-Oriol, P Llonch et al., 2021. Management and feeding strategies in early life to increase piglet performance and welfare around weaning: A review. Animals 11:302.

Cholewińska P, K Czyż, P Nowakowski et al., 2020. The microbiome of the digestive system of ruminants: A review. Animal Health Research Reviews 21:3–14.

de Las Hazas MCL, A Dávalos, 2022. Individualization and precision nutrition developments for the 21st century. Advances in Precision Nutrition, Personalization and Healthy Aging, Springer International Publishing, Cham, pp:25–50.

Downs SM, S Ahmed, T Warne et al., 2022. The global food environment transition based on the socio-demographic index. Global Food Security 33:100632.

González LA, I Kyriazakis, LO Tedeschi, 2018. Precision nutrition of ruminants: Approaches, challenges and potential gains. Animal 12:246–61.

Guo G, C Shen, Q Liu et al., 2019. Fermentation quality and digestibility of alfalfa silages. Animal Feed Science and Technology 257:114274.

Hanigan MD, VC Souza, R Martineau et al., 2021. Predicting ruminally undegraded and microbial protein flows from the rumen. Journal of Dairy Science 104:8685–8707.

Herrero M, P Havlík, H Valin et al., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences 110:20888–93.

Herrero M, PK Thornton, D Mason-D'Croz et al., 2020. Innovation can accelerate the transition towards a sustainable food system. Nature Food 1:266–72.

Kumar N, RS Chhokar, RP Meena et al., 2022. Challenges and opportunities in productivity and sustainability of rice cultivation system: A critical review in Indian perspective. Cereal Research Communications 50:573–601.

Kumar S, UK Singh, MH Ansari et al., 2025. Conventional and nonconventional feed resources enhancing animal production system. Grazing Strategies and Animal Production Systems, IntechOpen, pp:59–68.

Linh NT, NH Qui, A Triatmojo, 2022. The effect of nano-encapsulated herbal essential oils on poultry health. Archives of Razi Institute 77:2013.

Makkar HP, 2016. Smart livestock feeding strategies for harvesting triple gain: Planet, people and profit dimensions. Animal Production Science 56:519–34.

Markowiak P, K Śliżewska, 2018. The role of probiotics, prebiotics, and synbiotics in maintaining animal health and productivity. Animal Feed Science and Technology 233:88–99.

Mottet A, C De Haan, A Falcucci et al., 2017. Livestock: On our plates or eating at our table? Global Food Security 14:1–8.

Owens FN, DS Secrist, WJ Hill et al., 1998. Acidosis in cattle: A review. Journal of Animal Science 76:275–86.

Pagliari PH, M Wilson, HM Waldrip et al., 2020. Nitrogen and phosphorus characteristics of beef and dairy manure. Animal Manure: Production, Characteristics, Environmental Concerns, and Management, American Society of Agronomy, pp:45–62.

Ravindran V, AJ Cowieson, PH Selle, 2016. Phytase and phytate: Implications for poultry nutrition. Animal Feed Science and Technology 221:255–66.

Rehman A, L Jingdong, AA Chandio et al., 2017. Livestock production and population census in Pakistan: Relationship with agricultural GDP. Information Processing in Agriculture 4:168–77.

Saha SK, NN Pathak, 2021. Fundamentals of animal nutrition. Springer, Singapore, pp:219–46.

Singh N, R Gupta, A Awasthi et al., 2024. Feeding balanced ration for improving dairy cattle productivity: A review. Journal of Biological and Natural Sciences 16:26–31.

Smith A, T Jones, R Patel, 2020. Least-cost feed formulation and optimization algorithms in livestock nutrition. Journal of Animal Science 98:112.

Smith J, K Sones, D Grace et al., 2013. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. Animal Frontiers 3:6–13.
Sun Y, V Ramesh, F Wei et al., 2023. Methionine availability influences essential H3K36me3 dynamics during cell differentiation. bioRxiv 22:568331.
Tangorra FM, E Buoio, A Calcante et al., 2024. Internet of Things sensors application in dairy cattle farming. Animals 14:3071.
Tomberlin JK, C Miranda, C Flint et al., 2023. Nutrients limit production of insects for food and feed. Animal Frontiers 13:64–71.
Toplicean IM, AD Datcu, 2024. Bioeconomy in the agricultural sector and circular economy considerations. Agriculture 14:1143.
Windisch W, K Schedle, C Plitzner et al., 2008. Use of phytogenic products as feed additives for swine and poultry. Journal of Animal Science 86:140–8.
Yue Q, X Xu, J Hillier et al., 2017. Mitigating greenhouse gas emissions in agriculture. Journal of Cleaner Production 149:1011–9.
Zhang Y, F Li, M Yang et al., 2021. Nutrigenomics and nutrigenetics in livestock. Frontiers in Veterinary Science 8:642512.