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Review article

Sustainable livestock production systems are key to ensuring food security resilience in response to climate change

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Abstract

Importance of the work: The global dynamics encompassing production growth, food supply and the confronting scenario of climate change are profound indicators to harnessing livestock production to meet the anticipated demand of the world population of 9.7 billion in 2050.

Objectives: This review collected available research data associated with sustainable livestock production in association with food security and demand.

Results: The main pillars that will play pivotal roles are improvements in infrastructure, providing modern methodologies, enhancing supportive budgeting and fostering mutual networking. The world's population will continue to increase to 2050 requiring additional supplies of food for human consumption. Livestock production systems are an important contributor to the generation of protein-based products. Under the existing production scenario, both conventional and non-conventional resources are essential as inputs, especially the use of agricultural biomass. Practical interventions are necessary by stakeholders to mitigate methane emissions to reduce global warming. Strong and explicit recommendations by the government on livestock production require reinforcement among the stakeholders, along with the provision of supportive materials and marketing outlets. Food security efficiencies will be achieved through the production of meat, milk and eggs, as well by empowering the stakeholders, consisting of researchers, farmers and the industrial and non-governmental sectors. Furthermore, innovations associated with livestock production should be developed more by stakeholders.

Main findings: Most importantly, networking collaborations are highly encouraged. The outputs, outcomes and impacts should be notable if there is strong commitment and earnest deliberation. Implementations of findings on the ground are essential to provide greater food resilience under climate change impacts.

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Introduction

Providing food security has emerged as a critical concern for countries with varying levels of economic development, with agricultural production being essential to increasing food supply. The agricultural sector is important in increasing food availability and achieving food security (Pawlak and Kołodziejczak, 2020). While there is consensus that there will be greater demands for food globally in the ensuing decades, there is disagreement about whether global agriculture will be able to meet this demand by increasing the amount of food available (Food and Agriculture Organization of the United Nations (FAO), 2022a). In addition, the population of the world surpassed 7.6 billion in 2018 and is expected to grow to 9.2 billion by 2050, with a projected 59–102% increase in food demand (Haneklaus et al., 2016). Therefore, it is important to enhance agricultural productivity through the implementation of effective agriculture techniques to support the expanding population (Aroonsrimorakot and Laiphrakpam, 2023). Globally, higher temperatures will lead to an increased rate of evaporation from land surfaces and oceans (Elnashar and Elyamany, 2023). Farmers' livelihoods have been seriously impacted due to global warming, which is anticipated to have a detrimental impact on irrigation water, potentially reducing the adequacy of crop output. Specifically, Wankar et al. (2024) claimed that heat stress negatively impacted the quality and performance of animal products in all species of livestock. Notably, many scientists have investigated diverse approaches to modulating global warming solutions, such as utilizing agri-industrial residue that includes phytochemical compounds to mitigate methane gas emissions from ruminal fermentation (Shinagawa et al., 2023). Sikiru et al. (2024) reported that reduced methane emissions in cattle can increase economic growth through cost savings and enhanced productivity, creating new commercial prospects in the agriculture industry. Additionally, the prospective climatic predictions are expected to significantly impact pastures, grasslands, feedstuff quality and quantity, and biodiversity (Habib-ur-Rahman et al., 2022). For successful production, processing, marketing and consumption of safe and nutritious foods and other supplies, agricultural food systems organizations must carry out efficient climate resilience and adaptation behaviors that rely on ecological health and the sustainable use of renewable resources (FAO, 2022b). Eradicating global hunger, a Sustainable Development Goal, and ensuring food security for the future world population are major worldwide socioeconomic concerns. Enhancing comprehension of the many potential consequences and the primary factors influencing them is crucial for developing successful programs to guarantee worldwide food security (van Dijk et al., 2021). Global assessments primarily utilize four major indicators to evaluate the many aspects of food security: food demand, population at risk of hunger, food prices and malnutrition in childhood (Ishida et al., 2014). The livestock business plays a major role in agricultural development, ensuring food security and alleviating poverty. It is a crucial element in the global food web. The FAO (2006) states that livestock play a crucial role in supporting the livelihoods of around 1.3 billion people, ensuring their access to food and nutrition, and account for 40% of global agricultural production value. Ritchie and Roser (2017) stated that meat is a crucial nutritional source for a large portion of the global population. Meat supply has increased by over three times in the past 50 yr and there is a growing global demand for it and over 340 million t are produced worldwide each year. According to an FAO (2009) briefing report, world food production must increase by 70% to adequately feed the global population by 2050. Poore and Nemecek (2018) demonstrated that meat production has significantly greater environmental and climate impacts compared to plant-based meals. The livestock industry is a major contributor to the decrease in biodiversity in certain areas and is responsible for a substantial portion of the greenhouse gas emissions (GHG) produced by agriculture (Xu et al., 2021). The World Bank (2009) reported that continuing with normal operations without enhancing the capacity to enforce remedial actions will result in escalating issues. To have a meaningful and beneficial impact on humanity's future and well-being, the livestock sector must take coordinated action to raise awareness and build appropriate incentive frameworks. Investments in the sector should accompany this.

The aim of this paper was to identify and collect available research data associated with sustainable livestock production in association with food security and global population demand. The main pillars accounted to play pivotal roles are the improvements of infrastructure providing efficient and modern processes methodologies and enhancing supportive budgetary and fostering mutual net-workings.

Global livestock population and products

Agriculture and livestock have been crucial to human society from their origin and remain essential for human livelihood. For example, in developing nations, agriculture is the major source of subsistence for 80% of the people living in rural regions (Castañeda et al., 2018). More than 3 billion people globally still rely on agriculture, which involves the cultivation of plants and animals to provide food, feed, fiber and energy (FAO, 2021). Food and agriculture are essential components of a complete socioeconomic, cultural and environmental framework that play an important role in the global economy (Achterbosch et al., 2014; van Berkum et al., 2018). Currently, the world's population is rapidly increasing, having grown from around 2.5 billion individuals in 1950 to 8 billion in 2022, with projections indicating an increase to 8.5 billion by 2030 and 9.7 billion by 2050 (FAO, 2022a). With this demographic trend, the demand for food is anticipated to rise steeply, driven by both population growth and income-driven shifts in dietary preferences towards greater consumption of animal-source foods. As a result, the livestock sector faces major pressure to enhance the availability of safe and nutritious feed for animals, given the projected increase of over 60% in global demand for livestock products by 2050 (Makkar, 2018). Recently, FAOSTAT (2024) reported that the worldwide livestock population in 2022 consisted of over 3.0 billion poultry, 0.9 billion swine, 1.7 billion cattle and buffalo and 2.4 billion sheep and goats. Compared to populations in 2012, the populations of chickens, cattle, buffalo, goats and sheep increased by 30, 8 and 18%, respectively. However, the population of swine in 2022 decreased by 0.5% compared to 2012.

Association of microbiomes among crop, soil and livestock recycling

As the world's population continues to rise, increasingly food is being produced, leading to an inevitable accumulation of waste from agriculture. In order to ensure agricultural sustainability, human-food and health security, and adequate usage and valorizations, solutions must be established for handling the inadequate and/or incorrect management of these resources. (Koul et al., 2022). Agricultural strategists in developing countries suffer challenges in managing agricultural waste due to the inadequate availability of efficient strategy technologies. In addition, globally agricultural waste production is estimated to increase by approximately 5–10% annually, amounting to nearly 2 billion kg/yr (Al-Suhaibani et al., 2020). Once the harvest season was over, farmers would burn their crop residue on fields as a cheap means of disposal. Consequently, the emissions polluted the air and water in rural environments (Tran et al., 2024). Burning represents a major obstacle to agricultural production due to increased air pollution, short-lived climatic pollutants, environmental destruction and soil degradation (Raza et al., 2022). Alternatives include using agricultural biomass as biochar, bioplastic, in livestock management (feed, fodder, and bedding), generating energy from residue (electricity), and producing natural fuels from crop residue (biofuel and bioethanol). These options will not only advantageously affect the environment but also increase farmers' profits. This would also make managing crop residue more efficient (Mathur and Srivastava, 2019). Consequently, sanitary landfills, anaerobic digestion, composting, incineration, material and energy recovery and disposal are all necessary components of integrated solid waste management (Pratap et al., 2021). The term "microbiome" refers to the collective term for all the microorganisms found in a specific habitat, whether that habitat be a vast forest or marine ecosystem, a lagoon, plant or pit or even a more intimate space such as the human digestive tract. Notably, the waste contains microbiomes that break it down through active interaction. The idea of "Energy from Waste"

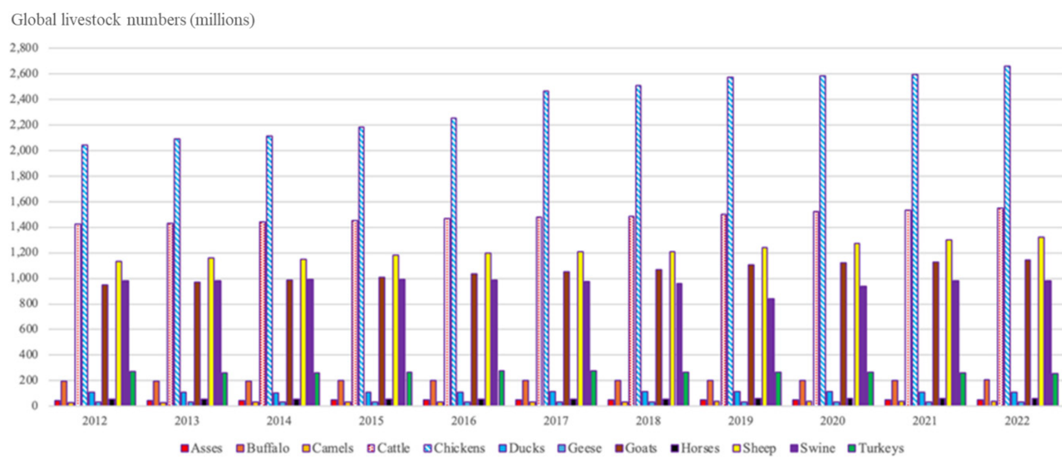

Fig. 1 Global livestock numbers of various livestock types from 2012 to 2022
Source: FAOSTAT (2024)

can address both the “waste” and the “energy” issues that plague the world today. Wastes from agriculture (rich in lignocellulosic and free sugars) are an appealing source of carbohydrates for developing bioprocesses for biobased goods and bioenergy production. The one ecologically conscious technique for dealing with driven residues is the biological conversion of waste, with the bacterial biomes found in these remnants degrading both basic and complicated compounds (Jurado et al., 2020). Inoculums of microorganisms that have been genetically modified could be utilized to hasten the bioconversion of organic matter. The efficacy of these modified stains surpasses that of the natural inoculum to efficiently generate homogeneous compositing (Iqbal et al., 2020). Agri-industrial waste has been manipulated by microorganisms for multiple purposes, including animal feed (Hou et al., 2023; Olagunju et al., 2023), biofertilizer and bioenergy (Kumar et al., 2023; Machineni and Anupoju, 2023).

Production systems across grazing, cut-and-carry to fattening

Additionally, the feeding strategy impacts the qualitative characteristics and fatty-acid composition of cattle. For example, normally, beef from animals that graze on grass contains higher levels of vitamin A and E, as well as conjugated linoleic acid, compared to animals that are fed a diet mostly consisting of concentrated feed (FAO, 2023). Hence, the integration of grazing and landless systems, at a regional or national scale, has the capacity to mitigate the environmental repercussions of beef production. In their study, Fernandez-Turren et al. (2020) provided evidence that grazing sheep restrict their range in order to enhance the preservation of native wildlife and flora by expanding protected areas. Reducing the intensity of GHG emissions, specifically the methane (CH_4) and nitrous oxide (N_2O) released per kilogram of meat or milk produced, is crucial. Consequently, it is essential to enhance productivity on pastures globally. Insufficient consumption of dry matter (DM) is a major limitation in pasture-based systems for animals with high productivity (Kolver, 2003). Hence, to enhance the quantity of dry matter produced by natural pasture and to ensure the long-term viability of livestock farming, it is recommended that livestock producers in study areas adopt a controlled-grazing strategy.

The cut-carry or zero grazing is a feeding technique where fresh grass is harvested and directly provided to cows that are kept housed. Usually, the fresh grass is harvested in an upright position using a specialized machine that also carries the grass from the field (Holohan et al., 2021). The practice of cut-carry has its origins in mainland Europe, where it is commonly used to enhance the diet of dairy cows in fully enclosed farms by providing them with fresh grass. Typically, these farms are more intensive than open-grazing farms, as they have larger herds and provide carefully managed diets of concentrated feed and stored forages, such as grass or maize silage, to ensure high milk production (Meul et al., 2012). However, there is limited knowledge regarding the utilization of cut-carry alongside traditional grazing systems in temperate settings. In the rainy season, animals are allowed to graze on communal or wooded areas, while frequently, grass is harvested and transported to feed the animals, thus preventing harm to cultivated land. Traditionally, farmers sell their cattle after the harvest when the plowing season concludes, as the cattle are in poor health and too old to be utilized during a drought. In the absence of grazing pasture, a method of fattening animals is used that relies on byproducts derived from the agricultural and industrial sectors (Wendimu et al., 2023).

Utilization of agricultural crop biomass

Agricultural crop biomass

Agricultural and forestry processes generate substantial quantities of waste originating from the harvestable output. The worldwide yearly production of biomass waste poses substantial challenges in terms of its management due to the potential adverse environmental effects associated with the disposal of biomass. Biomass waste streams have the potential to be used as raw materials for producing a wide range of products, including fuel, polymers, and building items. One present effort focused on investigating the biomass waste and its combination with mineralized CO_2 gas to produce sustainable construction materials (Chun and Brisson, 2015; United Nations Environment Programme, 2015).

Agricultural biomass wastes/residues refer to the primary remains of crops such as stalks, leaves, roots, fruit peels, and seed/nut shells. Typically, these materials are wasted or burned, foregoing their considerable potential as useful feed-stock material. There are challenges in accurately assessing the quantity of biomass generated by crops and distinguishing between what can be considered as a ‘loss’ (occurring during production, post-harvesting and processing) and what can be classified as ‘waste’ (resulting from retail or consumer activities), according to FAO (2011). A major issue is that the assessment of ‘food’ production typically focuses on the edible parts of a crop (harvest index) and overlooks non-edible biomass components, regardless of whether they are cultivated or not. Cultivated plants, such as sugarcane, frequently necessitate processing, which can result in the production of secondary and tertiary waste streams, in addition to the main biomass waste generated during harvesting (Schieber et al., 2001). Therefore, it can be posited that waste biomass should be a reasonably consistent by-product derived from the agricultural output for a specific crop and geographic area. Typically, in developing countries, the majority of biomass wastes are left untreated or unused, instead being allowed to degrade naturally or burned openly in the harvest field. However, certain waste residues produced from crops, such as sugarcane, rice, groundnuts, and coffee beans, are utilized as a source of fuel (Yevich and Logan, 2003). Cellulose, hemicelluloses and lignin-rich wastes have the potential to be utilized in the synthesis of chemicals, resins and enzymes (Khedari et al., 2003). Biomass waste, such as sugar bagasse, rice husk and wheat chaff, can be utilized, although there is limited exploitation of these resources (United Nations Environment Programme, 2016), and this crucial asset is still greatly underutilized. Therefore, since only a limited portion of the biomass waste produced is utilized as a raw material for industrial purposes and subsequently used to generate power, the rest has a negative influence on the atmosphere, as well as the quality of surface and groundwater, contributing to the spread of diseases.

Typically, the biomass potential is determined by aggregating the potential of waste and residual biomass derived from agricultural sources, such as leftover straw and livestock manure, as well as biomass obtained from forest harvesting, thinning and specific crops (Lozano-García et al., 2020). The sources of residual and waste biomass from the wood processing sector that are currently available and feasible in terms of both technology and economics are being exhausted at a fast pace; it is unlikely that there will be any rise in the amount of biomass obtained from this resource in the future (Algieri et al., 2019). The residual biomass potential of traditional agriculture is contingent upon the composition of conventional crops, the condition of livestock production in the specific region (which affects the use of residual biomass, such as forage and bedding straw, prioritizing them over energy recovery) and the constraints imposed by environmental and soil conservation regulations (Koul et al., 2022).

Utilization of biomass by livestock

Feed serves as the connection between livestock and land utilization, encompassing direct grazing as well as indirect utilization through the exchange of grain or forage. The four main types of feed for livestock are: 1) concentrated grain, typically given as feed; 2) grass, which can be directly grazed or used as silage; 3) infrequent feeds such forages, legumes and roadside grasses that are cut and carried; and 4) stovers, which are the fibrous wastes from crops (Herrero et al., 2008). On a global level, in 2000, livestock used around 4.7 billion t of feed biomass, with ruminants, such as cows and sheep, consuming the majority of this feed (3.7 billion t), followed by pigs and poultry (1 billion t); of this, grasses accounted for around 48% (2.3 billion t) of the biomass used by animals, with grains accounting for up to 28% (1.3 billion t) and intermittent feeds and stovers made up the remaining portion, serving as important sources of feed in specific areas (Blümmel et al., 2003). Intermittent feeding is important in South Asia, Latin America and the Caribbean, where the practice of supplementing with fodder crops is widespread (Blümmel et al., 2003), with stovers playing a crucial role as a primary source of feed in many developing areas, often constituting as much as 50% of the diet for ruminant animals in these places (Herrero et al., 2008; Valbuena et al., 2012).

Rumen microbiomes and fermentation efficiency

The rumen can be thought of as an anaerobic, methanogenic fermentation chamber full of microorganisms that can use cellulolytic feeds (such as grass, hay, silage and straw) and enhance the quantity they produce (Matthews et al., 2019). The rumen microbiome offers a crucial role in providing ruminants with the greater part of their diets and satisfies up to 90% of their metabolic requirements (Mizrahi and Jami, 2018). The rumen's microbial population is one of the animal kingdom's most varied gut ecosystems (Weimer, 2015), composed of not only bacteria (1×10^{10} to 1×10^{11} organisms/mL) but also archaea (1×10^{8} to 1×10^{9} organisms/mL), protozoa (1×10^{5} to 1×10^{6} organisms/mL), fungi (1×10^{3} to 1×10^{4} organisms/mL) and an as yet largely uncharacterized virome (Newbold and Ramos-Morales, 2020). The bacteria found in the rumen are located in three intersecting micro-environments: the rumen epithelial cells and protozoa, which contribute 5% of the microbial mass; the liquid phase, which makes up 25% of the microbiology; and the solid phase, which utilizes up to 70% of the microbial mass (Matthews et al., 2019). The rumen maintains an essentially stable pH of 6–7; however, this can differ based on the diet, which can alter the microbial populations and the amounts of volatile fatty acids that are produced by them (Matthews et al., 2019).

Factors influencing rumen microbiome

Diet

The ruminal microbial activity is influenced by the host's food, which also affects the host's feed efficiency and nutrient delivery. Therefore, a suitable diet is necessary for a healthy rumen environment to improve rumen microbiota and support ruminant growth and development. For example, compared to calves fed milk independently, calves fed milk and concentrate at age 28 d had a higher proportion of methanogens and bacteria that can easily break up dissolved fermentable carbohydrates (Sanjorjo et al., 2023). Forage material is the foundation of an adult ruminant's diet, primarily consisting of neutral detergent fiber (NDF). The concentration of cellulose, hemicellulose and lignin can be approximated from the amount of NDF. The concentrations of methanogens, anaerobic fungi and protozoa in the rumen of adult dairy cows fed an NDF-rich diet compared to a starch-rich diet indicated an increase in biodiversity (Wang et al., 2020).

Host effects

Recent research on mammalian host-microbe interactions has led to an increasing consensus that the microbial composition of the gastrointestinal system is a polygenic feature. Numerous research projects including the whole genome have been carried out to determine the host chromosomal regions that impact the composition and functionality of the microbiome in the rumen. According to Li et al. (2022) the primary bacterial phylum, the Bacteroidetes, was largely influenced by dietary manipulations and had low heritability estimates in cattle. However, some microbial characteristics of the rumen are inherited. Thus, rumen microbial taxonomy can be altered through genetic selection and breeding; however, but these methods are unlikely to have any impact if the rumen microbial community is influenced by external factors such as nutrition. Nevertheless, the study's confounding of a number of variables, including age and lactation cycles, has been associated with variations in the rumen microbiome.

Early life

The gastrointestinal tract of newly born calves has long been considered sterile, with microbial colonization starts immediately after contact with the mother's vaginal canal, fecal material, saliva, skin, and colostrum milk; however, mounting evidence of vertical transmission from a mother's placenta, umbilical cord or amniotic fluid during her pregnancy has cast doubt on this recently (Sanjorjo et al., 2023). In addition, as stated by Amin and Seifert (2021), the calf grows throughout the first year of its life, different microbial groups immediately occupy and colonize the rumen and its microbiota. An additional element influencing rumen microorganisms was the host's age. In the case of newborn calves and successive ages of 2 mth, 6 mth and 2 yr, the predominant rumen bacteria varied, with this stage of development encompassing the crucial transitional period of weaning. As reported by Du et al. (2023), the microbial diversity increased with changing feeding conditions when the animal was weaned at age 7–17 wk. Conversely, when the milk was replaced with a total mixed ration that included grass silage, the number of *Bacteriodetes* and *Fibrobacteres* increased to facilitate fiber degradation. Even the feeding method (suckled or. bottle-fed) could change the microbiome; bottle-feeding resulted in higher levels of *Escherichia coli* and *Shigella*, indicating an increased number of potential pathogens, as well as delaying the beginning of an anaerobic environment in the rumen. This shows that it is possible to manipulate the rumen's microbial community before birth and that treatments implemented during the early years of life can boost output and promote long-term health (Elolimy et al., 2019).

Meat and milk quality containing functional bioactive compounds

Meat and milk products are a great source of bioactive compounds that are beneficial to human health including vitamins, minerals, antioxidant peptides and fatty acids. There has been increasing demand to develop new, healthier animal products because of rising consumer awareness of food and the increased competition among animal producers worldwide (Pihlanto, 2006; Phupaboon et al., 2023). Dietary Guidelines for Americans in 2015–2020 recommended that consumption of polyunsaturated fatty acids consists of 5–10% energy from n-6 and 0.61–1.2% energy from n-3, with at least 0.5% energy from α-linolenic acid and 250 mg of eicosapentaenoic and docosahexaenoic acid each day (Siurana and Calsamiglia, 2016). To fulfill these demands, manufacturers include functionally enhanced supplements in animal diets and as direct additions to meat and milk products.

There is a great deal of nourishment in meat and/or milk, along with a wealth of bioactive components, including coenzyme Q10, glutathione, creatine, α-lipoic acid, taurine, L-carnitine, choline, conjugated linoleic acid (CLA) and omega-3 polyunsaturated fatty acids (PUFA) (Kulczyński et al., 2019). Numerous studies have documented the antioxidant and health-promoting qualities of these compounds, which are linked to their ability to lower blood pressure, reduce inflammation, lower cholesterol, activate the immune system and shield the body from oxidative stress (Kulczyński et al., 2019). The protein constituents of meat and milk have antioxidant properties due to their ability to scavenge reactive oxygen and nitrogen species, form complexes with metal ions and shield cells from harm (Pogorzelska-Nowicka et al., 2018). One of the goals of this review was to compile precise data regarding biological activity (as shown in Fig. 2), especially regarding poly-unsaturated fatty acids, such as α-lipoic acid, CLA, omega-3-fatty acid and other bioactive peptides, in either meat or milk samples.

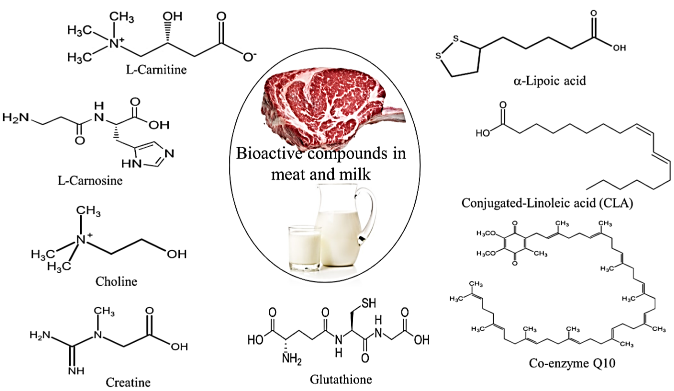

Fig. 2 Molecular compositions of specific bioactive compounds present in beef and milk

Future role of low-cost livestock and friendly-sustainable contributor to food chain scenario

In the near future, a larger global population surge will substantially increase the demand for food, requiring higher food production for both direct consumption and various value chains (FAO, 2019). Consequently, the unprecedented phenomenon of food insecurity has led to over 730 million people experiencing hunger, adversely affecting their well-being and livelihoods (FAO, 2022b). Currently, there has been increasing global agreement on the necessity to overhaul food systems to achieve crucial global objectives that intersect with the well-being of both humans and the Earth (Herrero et al., 2023). The Sustainable Development Goals (SDGs) of the United Nations emphasize the need to use resources more sustainably, minimize negative environmental impacts and to seek opportunities to restore degraded lands and depleted nutrients and/or biodiversity (FAO, 2018; Herrero et al., 2023). Concurrently, it is imperative to ensure universal access to more nutritious diets. Therefore, future food systems must offer a wide variety of affordable foods to ensure that everyone has access to diets of superior nutritional value. The livestock sector presents notable challenges due to its consumption of substantial resources, yet it provides nutrient-rich food with high-quality protein (Hendriks et al., 2023). This includes the sustainable utilization of natural resources, participation in international trade, and the changing dynamics of demand and supply for animal-source foods such as milk, meat and eggs. FAO (2018) indicated that seeking short-term production gains through excessive resource use may undermine long-term productivity. Although efficiency enhancements can lower emission levels, increased production may elevate overall GHGs. Shifting towards monogastric production might reduce emissions but could raise the demand for grains and legumes for animal feed, potentially affecting human food supplies. Van Zanten et al. (2018) stated the role of animals in the food system, often referred to as low-cost-livestock, should prioritize the conversion of biomass that is unsuitable or unwanted for direct human consumption into valuable products such as nutrient-rich food (meat, milk, and eggs) and manure (Table 1). This biomass includes materials from grasslands and leftovers such as crop residues from food crop harvesting, co-products

Table 1 Estimations of protein yield from animal-derived foods within food systems that prioritize low-cost livestock practices

Input: Leftover streams				Output: Animal source food			Reference
Grass-land	Crop residue	Co-product	Food waste	Product		Protein (g/d)	
				Type	g/d		
✓		✓	✓	Beef	51	10	Röös et al. (2017a,b)
				Milk	275	8	
				Pork	26	5	
✓		✓		Beef	10	2	Röös et al. (2016)
				Milk	257	8	
				Pork	46	9	
				Poultry	26	3	
✓	✓	✓		Beef	7	1	Schader et al. (2015)
				Milk	138	4	
				Pork	19	4	
				Egg	2	0	
✓	✓	✓		Beef	9	2	Smil (2014)
				Pork	12	2	
				Poultry	14	3	

Information only provided on protein production from low-cost livestock. No information compiled on land use.

from industrial processing of plant and animal-based foods, and losses and waste within the food system (Schader et al., 2015; Garnett et al., 2017). By repurposing these leftover materials, livestock can help to recycle nutrients back into the food system that would otherwise be lost during food production (Garnett et al., 2015). For example, ruminants play a vital role in converting grass products into milk, meat and manure, thereby contributing to the nutritional value of the food system (Van Zanten et al., 2018). By adopting this approach, arable land should be used primarily for the production of food crops, rather than for feed. Then, low-cost livestock would not consume human-edible biomass, such as grains, but convert leftover streams into valuable food, implying that the production of livestock feed could be largely decoupled from arable land. The availability of these biomass streams for livestock then determines the boundaries for livestock production and consumption (Van Zanten et al., 2018). Therefore, diets containing animal protein from low-cost livestock use less arable land (about 25% less) than a vegan diet and considerably less arable land than the meat-heavy current diets in high-income countries (Schader et al., 2015; Röös et al., 2017b; Van Zanten et al., 2018).

Conclusion

Animal-based foods (ABF) are essential to human health and well-being globally and are significantly contributed to by livestock production. Improvements in livestock production and management assist in achieving many of the important SDGs of the United Nations, such as no poverty, zero hunger, good health and well-being, enhancing industry innovation and infrastructure, and mitigating adverse climate change, with building partnerships helping to achieve these goals. Hence, sustainable livestock production is essential as a food protein source for global livelihoods.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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References

Achterbosch, T.J., Van Berkum, S., Meijerink, G.W., Asbreuk, H., Oudendag, D.A. 2014. Cash Crops and Food Security: Contributions to Income, Livelihood Risk and Agricultural Innovation. LEI Wageningen UR. Den Haag, the Netherlands.

Algieri, A., Andiloro, S., Tamburino, V., Zema, D.A. 2019. The potential of agricultural residues for energy production in Calabria (Southern Italy). Renew. Sustain. Energy Rev. 104: 1–14. doi.org/10.1016/j.rser.2019.01.001

Al-Suhaibani, N., Selim, M., Alderfasi, A., El-Hendawy, S. 2020. Comparative performance of integrated nutrient management between composted agricultural wastes, chemical fertilizers, and biofertilizers in improving soil quantitative and qualitative properties and crop yields under arid conditions. Agronomy 10: 1503. doi.org/10.3390/agronomy 10101503

Amin, N., Seifert, J. 2021. Dynamic progression of the calf's microbiome and its influence on host health. Comput. Struct. Biotechnol. J. 19: 989–1001. doi.org/10.1016/j.csbj. 2021.01.035

Aroonsrimorakot, S., Laiphrakpam, M. 2023. Green innovation to save water and energy for environmental sustainability in agricultural farming: A review. Agr. Nat. Resour. 57: 739–748. doi.org/10.34044/j.anres.2023.57.4.18

Blümmel, M., Zerbini, E., Reddy, B.V.S., Hash, C.T., Bidinger, F., Khan, A.A. 2003. Improving the production and utilization of sorghum and pearl millet as livestock feed: Progress towards dual-purpose genotypes. Field Crop. Res. 84: 143–158. doi.org/10.1016/S0378-4290(03)00146-1

Castañeda, A., Doan, D., Newhouse, D., Nguyen, M.C., Uematsu, H., Azevedo, J.P.A., World Bank Data for Goals Group. 2018. New profile of the global poor. World Dev. 101: 250–267. doi.org/10.1016/j.worlddev.2017.08.002

Chun, A.M.S., Brisson, I.E. 2015. Ground Rules in Humanitarian Design. John Wiley & Sons. New Jersey, UK.

Du, Y., Gao, Y., Hu, M., et al. 2023. Colonization and development of the gut microbiome in calves. J. Anim. Sci. Biotechnol. 14: 46. doi.org/10.1186/s40104-023-00856-x

Elnashar, W., Elyamany, A. 2023. Managing risks of climate change on irrigation water in arid regions. Water Resour. Manage. 37: 2429–2446. doi.org/10.1007/s11269 -022-03267-1

Elolimy, A., Alharthi, A., Zeineldin, M., Parys, C., Helmbrecht, A., Loor, J.J. 2019. Supply of methionine during late-pregnancy alters fecal microbiota and metabolome in neonatal dairy calves without changes in daily feed intake. Front. Microbiol. 10: 2159. doi.org/10.3389/fmicb.2019.02159

Food and Agriculture Organization of the United Nations (FAO). 2006. World Agriculture: Towards 2030/2050. Interim report. Global Perspective Studies Unit, Food and Agriculture Organization of the United Nations. Rome, Italy.

FAO. 2009. How to Feed the World in 2050: High-Level Expert Forum. Food and Agriculture Organization of the United Nations. Rome, Italy.

FAO. 2011. Global forest products facts and figures. http://www.fao.org/fileadmin/user_upload/newsroom/docs/2011%20GFP%20Facts%20and%20Figures.pdf, 16 February 2024.

FAO. 2018. The 10 elements of agroecology. Guiding the transition to sustainable food and agricultural systems. http://www.fao.org/3/i9037en/i9037en.pdf, 16 February 2024.
FAO. 2021. FAO Statistical Yearbook–World Food and Agriculture. Food and Agriculture Organization of the United Nations. Rome, Italy.
FAO. 2022a. In brief to the state of food and agriculture. Leveraging automation in agriculture for transforming agrifood systems. Food and Agriculture Organization of the United Nations. Rome, Italy. doi.org/10.4060/cc2459en
FAO. 2022b. FAO Strategy on Climate Change 2022–2031. Food and Agriculture Organization of the United Nations. Italy, Rome.
FAO. 2023. Contribution of Terrestrial Animal Source Food to Healthy Diets for Improved Nutrition and Health Outcomes: An Evidence and Policy Overview on the State of Knowledge and Gaps. Food and Agriculture Organization of the United Nations. Rome, Italy.
FAOSTAT. 2024. The Food and Agriculture Organization Corporate Statistical Database. Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL, 17 February 2024.
Fernandez-Turren, G., Repetto, J.L., Arroyo, J.M., Pérez-Ruchel, A., Cajarville, C. 2020. Lamb fattening under intensive pasture-based systems: A review. Animals 10: 382. doi.org/10.3390/ani10030382
Garnett, T., Godde, C., Muller, A., et al. 2017. Grazed and confused? Ruminating on Cattle, Grazing Systems, Methane, Nitrous Oxide, the Soil Carbon Sequestration Question–and What it All Means for Greenhouse Gas Emissions. Food Climate Research Network (FCRN). University of Oxford. Oxford, UK.
Garnett, T., Röös, E., Little, D.C. 2015. Lean, Green, Gean, Obscene...? What is Efficiency? and is it Sustainable? Animal Production and Consumption Reconsidered. Food Climate Research Network (FCRN). Oxford, UK.Habib-ur-Rahman, M., Ahmad, A., Raza, A., et al. 2022. Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. Front. Plant Sci. 13: 925548. doi.org/10.3389/fpls.2022.925548
Haneklaus, S., Lilienthal, H., Schnug, E. 2016. 25 years precision agriculture in Germany-A retrospective. In: Proceedings of the 13th International Conference on Precision Agriculture, St. Louis, MO, USA, pp. 1–9.
Hendriks, S., Soussana, J.F., Cole, M., Kambugu, A., Zilberman, D. 2023. Ensuring access to safe and nutritious food for all through the transformation of food systems. In: von Braun, J., Afsana, K., Fresco, L.O., Hassan, M.H.A. (Eds.). Science and Innovations for Food Systems Transformation. Springer. Cham, the Netherland, pp. 31.
Herrero, M., Thornton, P.K., Kruska, R., Reid, R.S. 2008. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. Agric. Ecosyst. Environ. 126: 122–137. doi.org/10.1016/j.agee.2008.01.017
Herrero, M., Mason-D'Croz, D., Thornton, P.K., et al. 2023. Livestock and sustainable food systems: Status, trends, and priority actions. In: von Braun, J., Afsana, K., Fresco, L.O., Hassan, M.H.A. (Eds.). Science and Innovations for Food Systems Transformation. Springer. Cham, Switzerland, pp. 375–399. doi.org/10.1007/978-3-031-15703-5_20
Holohan, C., Russell, T., Mulligan, F.J., Pierce, K.M., Lynch, M.B. 2021. A survey analysis of farmer practices and perceptions of zero-grazing on Irish dairy farms. J. Dairy Sci. 104: 5665–5674. doi.org/10.3168/jds.2020-19164
Hou, Z., Liu, J., Cai, M., et al. 2023. The volatile organic compounds and palatability of mixed ensilage of marigold (*Tagetes erecta* L.) crop residues. Sci. Rep. 13: 2080. doi.org/10.1038/s41598-023-28511-5
Iqbal, N., Agrawal, A., Dubey, S., Kumar, J. 2020. Role of decomposers in agricultural waste management. In: Basso, T.P., Basso, T.O., Basso, L.C. Biotechnological Applications of Biomass. IntechOpen. London, UK.
Ishida, H., Kobayashi, S., Kanae, S., et al. 2014. Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. Environ. Res. Lett. 9: 064014. doi.org/10.1088/1748-9326/9/6/064014
Jurado, M.M., Camelo-Castillo, A.J., Suárez-Estrella, et al.2020. Integral approach using bacterial microbiome to stabilize municipal solid waste. J. Environ. Manage. 265: 110528. doi: 10.1016/j.jenvman.2020.110528
Khedari, J., Charoemvai, S., Hiruanlabh, J. 2003. New insulating particle boards from durian peel and coconut coir. J. Build. Environ. 38: 435–441. doi.org/10.1016/S0360- 1323(02)00030-6
Kolver, E.S. 2003. Nutritional limitations to increased production on pasture-based systems. Proc. Nutr. Soc. 62: 291–300. doi.org/10.1079/PNS2002200
Koul, B., Yakoob, M., Shah, M.P. 2022. Agricultural waste management strategies for environmental sustainability. Environ. Res. 206: 112285. doi.org/10.1016/j.envres. 2021.112285
Kulczyński, B., Sidor, A., Gramza-Michałowska, A. 2019. Characteristics of selected antioxidative and bioactive compounds in meat and animal origin products. Antioxidants 8: 335. doi.org/10.3390/antiox8090335
Kumar, V.S., Sarkar, D.J., Sarkar, S.D., Banerjee, T., Roy, S., Talukder, A., Das, B.K. 2023. Valorisation of banana pseudostem waste-based hydrochar for sustainable biodiesel production from microalgae. Bioenergy Res. 17: 1104–1117. doi.org/10.1007/s12155-023-10682-8
Li, C., Cui, Q., Li, Y., Zhang, K., Lu, X., Zhang, Y. 2022. Effect of LDPE and biodegradable PBAT primary microplastics on bacterial community after four months of soil incubation. J. Hazard. Mater. 429: 128353. doi.org/10.1016/j.jhazmat.2022.128353
Lozano-García, D.F., Santibañez-Aguilar, J.E., Lozano, F.J., Flores-Tlacuahuac, A. 2020. GIS-based modeling of residual biomass availability for energy and production in Mexico. Renew. Sustain. Energy Rev. 120: 109610. doi.org/10.1016/j.rser.2019.109610
Machineni, L., Anupoju, G.R. 2023. Optimization of biomethane production from sweet sorghum bagasse using artificial neural networks combined with particle swarm algorithm. Environ. Sci. Pollut. Res. Int. 30: 114095–114110. doi.org/10.1007/s11356-023-30451-6
Makkar, H.P.S. 2018. Review: Feed demand landscape and implications of food-not feed strategy for food security and climate change. Animal 12: 1744–1754. doi.org/10.1017/S175173111700324X
Mathur, R., Srivastava, V.K. 2019. Crop residue burning: Effects on environment. In: In: Shurpali, N., Agarwal, A., Srivastava, V. (Eds.). Greenhouse Gas Emissions. Energy, Environment, and Sustainability. Springer, Singapore, pp. 127–140. doi.org/10.1007/978-981-13-3272-2_9
Matthews, C., Crispie, F., Lewis, E., Reid, M., O'Toole, P.W., Cotter, P.D. 2019. The rumen microbiome: a crucial consideration when optimising milk and meat production and nitrogen utilisation efficiency. Gut Microbes 10: 115–132. doi.org/10.1080/ 19490976.2018.1505176
Meul, M., Van Passel, S., Fremaut, D., Haesaert, G. 2012. Higher sustainability performance of intensive grazing versus zero-grazing dairy systems. Agron. Sustain. Dev. 32: 629–638. doi.org/10.1007/s13593-011-0074-5
Mizrahi, I., Jami, E. 2018. Review: The compositional variation of the rumen microbiome and its effect on host performance and methane emission. Animal 12: s220–s232. doi.org/10.1017/S1751731118001957
Newbold, C.J., Ramos-Morales, E. 2020. Ruminal microbiome and microbial metabolome: effects of diet and ruminant host. Animal 14: s78–s86. doi.org/10.1017/S1751731119003252
Olagunju, L.K., Isikhuemhen, O.S., Dele, P.A., et al.2023. Effects of the incubation period of *Pleurotus ostreatus* on the chemical composition and nutrient availability of solid-state-fermented corn stover. Animals 13: 2587. doi.org/10.3390/ani13162587

Pawlak, K., Kołodziejczak, M. 2020. The role of agriculture in ensuring food security in developing countries: Considerations in the context of the problem of sustainable food production. Sustainability 12: 5488. doi.org/10.3390/su12135488

Phupaboon, S., Hashim, F.J., Phumkhachorn, P., Rattanachaikunsopon, P. 2023. Molecular and biotechnological characteristics of proteolytic activity from *Streptococcus thermophilus* as a proteolytic lactic acid bacteria to enhance protein-derived bioactive peptides. AIMS Microbiol. 9: 591. doi.org/10.3934/microbiol.2023031

Pihlanto, A. 2006. Antioxidative peptides derived from milk proteins. Int. Dairy J. 16: 1306–1314. doi.org/10.1016/j.idairyj.2006.06.005

Pogorzelska-Nowicka, E., Atanasov, A.G., Horbańczuk, J., Wierzbicka, A. 2018. Bioactive compounds in functional meat products. Molecules 23: 307. doi.org/10.3390/ molecules23020307

Poore, J., Nemecek, T. 2018. Reducing food's environmental impacts through producers and consumers. Science 360: 987–992. doi.org/10.1126/science.aaq0216

Pratap, V., Bombaywala, S., Mandpe, A., Khan, S.U. 2021. Solid waste treatment: Technological advancements and challenges. In: Karri, R.R., Ravindran, G., Dehghani, M.H. (Eds.). Soft Computing Techniques in Solid Waste and Wastewater Management. Elsevier. Amsterdam, the Netherlands, pp. 215–231. doi.org/10.1016/B978-0-12-824463-0.00014-8

Raza, M.H., Abid, M., Faisal, M., Yan, T., Akhtar, S., Adnan, K.M.M. 2022. Environmental and health impacts of crop residue burning: Scope of sustainable crop residue management practices. Int. J. Environ. Res. Public Health 19: 4753. doi.org/10.3390/ijerph19084753

Ritchie, H., Roser, M. 2017. Micronutrient deficiency. Our World in data. https://www.ourworldindata.org/micronutrient-deficiency, 24 October 2020.

Röös, E., Bajzelj, B., Smith, P., Patel, M., Little, D., Garnett, T. 2017a. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Glob. Environ. Change 47: 1–12. doi.org/10.1016/j.gloenvcha.2017.09.001

Röös, E., Bajzelj, B., Smith, P., Patel, M., Little, D., Garnett, T. 2017b. Protein futures for Western Europe: Potential land use and climate impacts in 2050. Reg. Environ. Change 17: 367–377. doi.org/10.1007/s10113-016-1013-4

Röös, E., Patel, M., Spangberg, J., Carlsson, G., Rydhmer, L. 2016. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 58: 1–13. doi.org/10.1016/j.foodpol.2015.10.008

Sanjorjo, R.A., Tseten, T., Kang, M.K., Kwon, M., Kim, S.W. 2023. In pursuit of understanding the rumen microbiome. Fermentation. 9: 114. doi.org/10.3390/ fermentation9020114

Schader, C., Muller, A., El-Hage Scialabba, N., et al. 2015. Impacts of feeding less food competing feedstuffs to livestock on global food system sustainability. J. R. Soc. Interface. 12: 20150891. doi.org/10.1098/rsif.2015.0891

Schieber, A., Stintzing, F.C. Carle, R. 2001. By-products of plant food processing as a source of functional compounds–Recent developments. Trends Food Sci. Technol. 12: 401–413. doi.org/10.1016/S0924-2244(02)00012-2

Shinagawa, K., Boonesaen, P., Khongpradit, A., Sawanon, S., Suzuki, Y., Koike, S., Kobayashi, Y. 2023. Potency of Indian gooseberry peel supplementation for suppressing rumen methane production via alteration of rumen microbiota: Batch culture evaluations. Agr. Nat. Resour. 57: 1043–1052. doi.org/10.34044/j.anres. 2023.57.6.15

Sikiru, A., Michael, A.O., John, M.O., Egena, S.S.A., Oleforuh-Okoleh, V.U., Ambali, M.I., Muhammad, I.R. 2024. Methane emissions in cattle production: Biology, measurement and mitigation strategies in smallholder farmer systems. Environ. Dev. Sustain. 2024. doi.org/10.1007/s10668-024-04939-1

Siurana, A., Calsamiglia, S. 2016. A metaanalysis of feeding strategies to increase the content of conjugated linoleic acid (CLA) in dairy cattle milk and the impact on daily human consumption. Anim. Feed Sci. Technol. 217: 13–26. doi.org/10.1016/j.anifeedsci. 2016.04.013

Smil, V. 2014. Eating meat: Constants and changes. Glob. Food Secur. 3: 67–71. doi.org/10.1016/j.gfs.2014.06.001

Tran, T.H., Nguyen, T.B.T., Le, H.S.T., Phung, D.C. 2024. Formulation and solution technique for agricultural waste collection and transport network design. Eur. J. Oper. Res. 313: 1152–1169. doi.org/10.1016/j.ejor.2023.08.052

United Nations Environment Programme. 2015. Converting waste agricultural biomass into a resource. United Nations Environment Programme, Division of Technology, Industry and Economics International Environmental Technology Centre, Osaka/Shiga, Japan. www.unep.org/ietc/Portals/136/Publications/Waste%20Management/WasteAgriculturalBiomassEST_Compendium.pdf, 16 February 2024.

United Nations Environment Programme. 2016. Global Partnership on Waste Management. http://web.unep.org/gpwm/ what-we-do/waste-agricultural-biomass. 16 February 2024.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., et al. 2012. Conservation agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. Field Crops Res. 132: 175–184. doi.org/10.1016/j.fcr.2012.02.022

van Berkum, S., Dengerink, J., Ruben, R. 2018. The Food Systems Approach: Sustainable Solutions for a Sufficient Supply of Healthy Food. Wageningen Economic Research. Den Haag, the Netherlands.

van Dijk, M., Morley, T., Rau, M.L., Saghai, Y. 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nat. Food. 2: 494–501. doi.org/10.1038/s43016-021-00322-9

Van Zanten, H.H.E., Herrero M, Hal O.V, et al. 2018. Defining a land boundary for sustainable livestock consumption. Glob. Change Biol. 24: 4185–4194. doi.org/10.1111/gcb. 14321

Wang, L., Li, Y., Zhang, Y., Wang, L. 2020. The effects of different concentrate-to-forage ratio diets on rumen bacterial microbiota and the structures of Holstein cows during the feeding cycle. Animals 10: 957. doi.org/10.3390/ani10060957

Wankar, A.K., Bhangale, G.N., Rindhe, S.N., Kumawat, B.L., Shafi, T.A. 2024. Heat stress in beef cattle: Climate change and the global scenario – A review. Ann. Anim. Sci. doi.org/10.2478/aoas-2024-0026

Weimer, P.J. 2015. Redundancy, resilience, and host specificity of the ruminal microbiota: implications for engineering improved ruminal fermentations. Front. Microbiol. 6: 296. doi.org/10.3389/fmicb.2015.00296

Wendimu, A., Tekalign, W., Bojago, E., Zemarku, Z. 2023. Beef cattle fattening practices and marketing system in tropical highlands of Ethiopia. J. Agric. Food Res. 14: 100806. doi.org/10.1016/j.jafr.2023.100806

World Bank. 2009. Minding the stock: Bringing Public Policy to Bear on Livestock Sector Development. Washington DC, USA.

Xu, X., Sharma, P., Shu, S., et al. 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat. Food. 2: 724–732. doi.org/10.1038/s43016-021-00358-x

Yevich, R., Logan, J.A. 2003. An assessment of biofuel use and burning of agricultural waste in the developing world. Glob. Biogeochem. Cycles 17: 1095. doi.org/10.1029/2002GB 001952