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Navigating The Challenges and Best Practices in Sustainable Livestock Production

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Abstract

The livestock sector contributes substantially to global food and nutrition security, but its rapid intensification places increasing pressure on land, water, waste systems, public health, and greenhouse gas (GHG) emissions. This paper reviews the major sustainability challenges associated with livestock production and synthesises green technology and circular economy practices that can support more sustainable operations. A narrative review approach was used, supported by secondary data analysis from international datasets and reports, including OECD-FAO, Worldometer, the Food and Agriculture Organization (FAO), and Ritchie and Roser. Production trends were visualised, Pearson's correlation coefficient was calculated using OriginPro, and manure, biogas, and electricity potentials were estimated from published conversion factors. The review shows that rising human population and livestock production intensify the demand for resource-efficient waste, water, and emission management, while projected manure generation offers significant potential for biogas and renewable electricity production. Waste hierarchy practices, manure valorisation, wastewater treatment, water conservation, and circular economy integration are identified as key pathways for reducing pollution and improving resource recovery. Adopting these practices is essential for balancing food security with environmental sustainability.

1. Introduction

The livestock sector is an integral part of the global food system by providing essential commodities such as meat, milk, eggs, and cheese for human consumption. Beyond food security, livestock products also support nutrition security by delivering high-quality protein and micronutrients that are crucial for human growth and health (Smith et al., 2013). As the world population continues to increase, the demand for food will also rise. By 2050, when the global population is expected to reach about 9.3 billion, world food production will need to increase by 62% from the current 8.2 billion tonnes a year (FAO, 2014). The livestock sector therefore faces increasing pressure to improve productivity. However, the environmental impacts of livestock activities, including land use, water consumption, and the release of greenhouse gases (GHGs), must be considered when meeting this demand (Baldi & Gottardo, 2017).

Natural resources are vital for the operation of livestock farms. Among human activities, the livestock sector uses substantial natural resources, particularly land and water (FAO, 2009; Agregán et al., 2021). However, competition for water and land is expected to intensify in the future, thereby affecting livestock production

(Thornton, 2010). Livestock uses almost 80% of agricultural land for grazing and feed production, while one-third of global cereal consumption is dedicated to livestock feed (FAO, 2009; Alexandratos & Bruinsma, 2012). At the global scale, agricultural activities use 86% of blue and green water, of which approximately 41% is used by the livestock sector for feed production (Doreau et al., 2012; Heinke et al., 2020). Increasing livestock production without appropriate mitigation measures may therefore lead to further depletion of these resources. In addition, climate change and extreme weather conditions can disrupt livestock production and intensify food crises (Escarcha, 2018; FSIN, 2022).

Although the livestock sector is essential for food production and rural economic activities, it is also associated with climate change and pollution. Greenhouse gases (GHGs), including methane and nitrous oxide, have global warming potentials 28 times and 265 times greater than carbon dioxide, respectively, and are emitted from livestock activities (Grossi et al., 2019; Leitner et al., 2020). Currently, about 18% or 7.1 Gt carbon dioxide equivalent (CO2-eq) of GHG emissions from human activities are largely contributed by the livestock sector (Steinfeld et al., 2006; FAO, 2021). Due to rapid growth in demand for meat products, the livestock sector has also become a prominent source of water pollution (Hu & Cheng, 2013; Stoyanova & Harizanova, 2019). Animal waste, antibiotics, hormones, fertilisers, and pesticides are among the pollutants associated with livestock activity (Steinfeld et al., 2006). About 25% of global sub-basins are considered pollution hotspots, with livestock identified as a major source of pollutants (Li et al., 2022b).

By 2050, it is projected that there will be approximately 43 billion livestock animals, including cattle, buffalo, sheep, goats, pigs, and poultry, globally (Alexandratos & Bruinsma, 2012). This number is several times larger than the human population and raises concerns about competition for finite natural resources for both human food and animal feed. Without technological progress and mitigation efforts, the environmental impacts of the food system could increase by 50% to 90% by 2050 (Springmann et al., 2018). Hence, the adoption of green technology and eco-friendly practices in the livestock sector should be promoted to ensure that livestock production can grow sustainably without placing additional pressure on the environment. This paper reviews the challenges that necessitate sustainable livestock production and discusses best practices and circular economy approaches that can be adopted by the sector.

2. Methodology

This paper adopts a narrative review approach supported by secondary data analysis. The review was designed to synthesise current knowledge on sustainable livestock production, with specific attention to environmental challenges, green technology applications, waste and water management, and circular economy practices. The secondary data analysis was included to provide quantitative context for the discussion on livestock production trends, population growth, manure generation, biogas potential, and electricity generation potential.

2.1 Literature Search Strategy

The literature search was conducted using academic and institutional sources, including Google Scholar, ScienceDirect, FAO and OECD-FAO repositories, government and institutional reports, and relevant peer-reviewed journal articles. The main keywords used in the search included “sustainable livestock production”, “livestock waste”, “livestock wastewater”, “greenhouse gas emissions”, “manure management”, “biogas”, “green technology”, “circular economy”, “food security”, and “livestock environmental impact”. Priority was given to studies and reports that discussed livestock production, waste management, water management, circular economy models, public health, and sustainability practices. Articles and reports were included when they were relevant to livestock systems, environmental management, or resource recovery. Sources that were unrelated to livestock production, lacked sufficient methodological or technical detail, or did not contribute directly to the themes of the review were excluded.

2.2 Secondary Data Analysis

Secondary data were used to support the narrative review and to illustrate trends in livestock production and resource recovery potential. Global livestock commodity production data were obtained from the OECD-FAO Agricultural Outlook 2021-2030 (OECD/FAO, 2021), while human population, livestock population, and meat consumption data were compiled from Worldometer (2022), FAO-related projections, Alexandratos and Bruinsma (2012), and Ritchie and Roser (2017). Pearson’s correlation coefficient (r) was calculated using OriginPro version 8 to evaluate the relationship between human population growth and selected livestock population trends. Daily manure production was estimated by multiplying the projected number of livestock animals by published daily manure production rates per head. Potential biogas production and electricity generation were then estimated using the published conversion assumptions that 1 metric ton of manure can produce approximately 36 m3 of biogas and that the resulting biogas can generate about 63.8 kWh of electricity

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(Recebli et al., 2015; Khalil et al., 2019). These calculations were intended to provide indicative estimates rather than predictive modelling.

3. The Challenges in Livestock Sector

The livestock sector provides food security, but it can also affect the environment if it is not managed properly. Fig. 1 summarises five interrelated challenges faced by the livestock sector: food security, resource management, waste management, public health, and GHG emissions. The figure highlights that sustainable livestock production requires not only sufficient food supply, but also responsible management of resources, pollutants, and health risks. The main objective of livestock rearing is food production; therefore, the first challenge is to provide sufficient food and ensure food security. In addition to rising food prices, many countries face food insecurity and low self-sufficiency levels (SSL) in producing their own food. It is estimated that about 2.3 billion people in the world are facing food insecurity, predominantly in rural areas (FAO, 2025b). Currently, the livestock sector contributes 33% and 17% of global protein intake and calorie intake, respectively (FAO, 2018). To ensure food security and meet the demand of a growing population, livestock food output can be increased through intensification, which increases yield per hectare, and extensification, which expands land use (Michalk et al., 2019). The second challenge is related to the intensive use of resources for livestock production. Livestock is estimated to use about 2.5 billion hectares of land, while about 40% or 560 million hectares of global arable land is used for livestock feed production (Mottet et al., 2017). Land conversion for livestock production may also result in land-use changes such as deforestation, biodiversity loss, and soil degradation (FAO, 2018).

Fig. 1 *The challenges faced by the livestock sector*

The waste generated from livestock production is also a key challenge for the sector. The intensification of livestock production has resulted in large quantities of manure, slaughterhouse waste, and agricultural residues, which lead to higher excretion of nitrogen, phosphorus, and organic matter that can pollute the environment (Vasmara & Martini, 2025). Livestock wastewater is a significant source of non-point agricultural pollution that can affect the environment and water resources (Hu et al., 2020; Li et al., 2022a). Proper treatment of livestock waste is necessary because it may contain pollutants that affect the environment and public health, including antibiotics, veterinary drugs, heavy metals, and pathogens. Livestock wastewater also has high chemical oxygen demand and nutrient loads that may pollute freshwater and cause eutrophication (Vasmara & Martini, 2025). Besides the overuse and misuse of antibiotics for livestock production, the majority of antibiotics given to livestock are excreted and may persist in the environment, contributing to antimicrobial resistance (AMR) (Zhang et al., 2024; Trinchera et al., 2025). With the intensification of livestock production to address food security, livestock waste management must also be scaled up to avoid environmental pollution, public health concerns, and deterioration of the quality of life of nearby residents.

Another major challenge for livestock production is the emission of GHG. The direct emission of GHG from livestock comes from enteric fermentation and manure management, while the indirect emission is from feed production. During enteric fermentation, the specific microorganisms in the rumen produce methane as a by-product during digestion, while anaerobic decomposition of manure also produces methane along with denitrification of manure which produces nitrous oxide (Sejian et al., 2016). While livestock production emits GHG which impacts climate change, its productivity is also affected by the global warming from climate change. Climate change can cause heat stress in livestock which leads to decreased feed intake, lower milk production, reduced reproductive performance, and changes in mortality and immune system function (Cheng et al., 2022). Among the ways that is being done to navigate this issue is by optimising animal nutrition, improving manure management, integrating agroforestry systems, as well as adopting smart technologies to strengthen climate change resilience and support decision-making in livestock production (Jiménez et al., 2025).

These challenges require us to shift towards sustainable livestock practices. We need to find a way to balance the need for livestock intensification with ways to mitigate the environmental impact. The urgent need for improved animal-based food production methods, resource management, and waste treatment is evident, especially as the world struggles with rising food prices and an increasing population.

4. The Need for Sustainable Livestock Practices

The importance of the livestock sector can be further observed through the time-series trend of livestock commodity production from 2000 to 2024, as presented in Fig. 2. The figure shows that worldwide production of selected livestock commodities has increased steadily over the last two decades, with poultry meat demonstrating the most rapid growth compared with other meat categories. Poultry and pig meats recorded the highest global increases, while cattle meat remained comparatively stable over the years (González et al., 2020). Demand for livestock commodities is expected to increase by 60% to 70%, with meat production alone projected to grow by nearly 200 million tonnes or 76% by 2050 (Alexandratos & Bruinsma, 2012; Makkar, 2018). By 2033, poultry meat is expected to contribute 43% of protein consumption from animal-based meat, followed by pig, bovine, and sheep meats (OECD/FAO, 2024). Poultry meat production has increased by 4% per annum, while per capita consumption of poultry meat increased from 2.9 kg in 1961 to 15.6 kg in 2018 (Govoni et al., 2021). Consumers generally prefer poultry meat because of its lower price and healthier combination of protein and fat, as well as its lower GHG emissions and fewer environmental pollutants compared with some other meat sources (González et al., 2020; OECD/FAO, 2024).

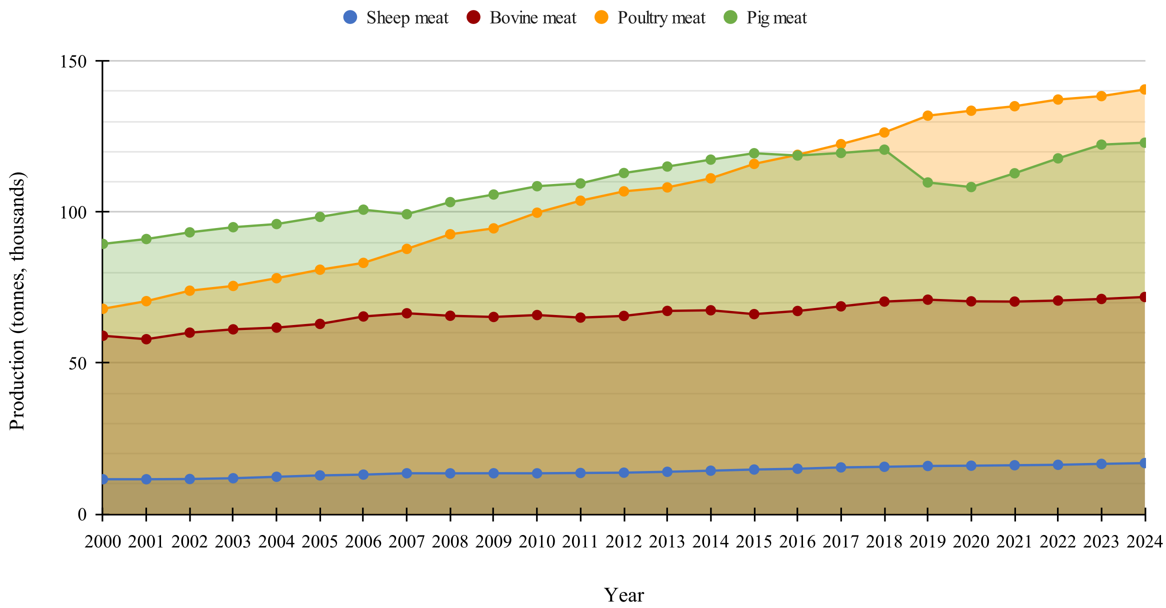

Fig. 2 *Production of selected livestock commodities worldwide for the year 2000-2024*

4.1 Meat Consumption

Fig. 3 presents the relationship between human population growth and global per capita meat consumption from 2000 to 2024. The figure shows that human population and selected meat consumption trends generally increased during the study period, although the rate of increase differed across meat categories. In 2004, the average per capita meat consumption was 30.58 kg with a global population of 6.5 billion, while in 2020 it was recorded at 34.01 kg with a population of 7.8 billion. The relationship between human population from 2004 to 2024 and the selected livestock population, comprising buffalo, cattle, goats, sheep, pigs, and poultry, produced a strong positive correlation (r = 0.999). This result indicates that livestock population tends to grow as human population increases, reinforcing the need for sustainable production and waste management strategies.

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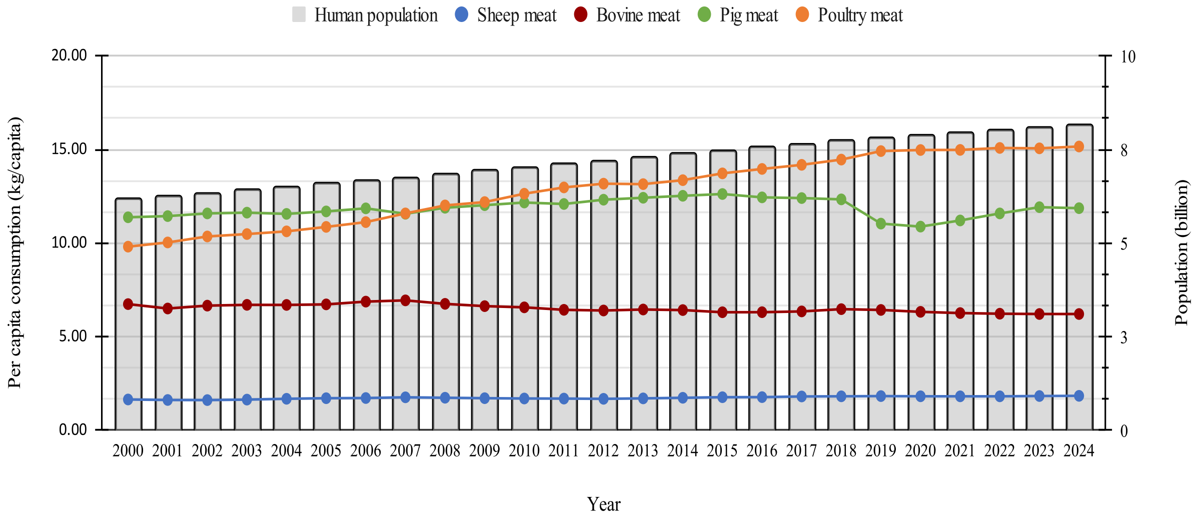

Fig. 3 *Per capita meat consumption and human population for the year 2000 – 2024*

4.2 Waste Generation

The relationship between human population and livestock can generally be understood as directly proportional. As the human population increases, livestock populations also increase to meet food demand. Fig. 4 illustrates this relationship from a waste perspective by showing that livestock populations and livestock faecal waste can exceed human waste burdens. According to FAO, livestock accounts for 86% of the total faecal waste generated in the world, while 14% is produced by humans (Bartram, 2012). While human waste is managed through sanitary systems in many parts of the world, much livestock faecal waste does not pass through proper waste management systems despite its larger volume. As stewards of the Earth, human beings have the responsibility to manage natural resources and preserve the environment (Szücs et al., 2009). Therefore, livestock waste should be handled properly to prevent environmental pollution and avoid the spread of zoonotic diseases. Pathogens such as E. coli, Salmonella, Clostridium, and Campylobacter are found in animal excreta and can cause gastrointestinal diseases when water sources are contaminated with livestock waste (Saxena & Sewak, 2016).

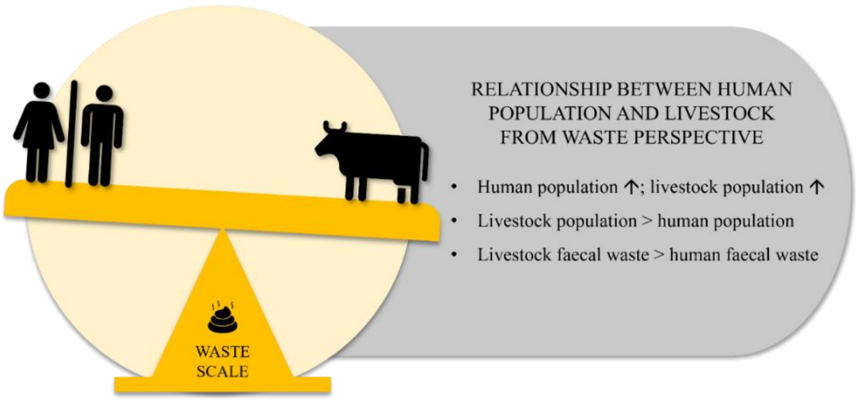

Fig. 4 *The relationship of human population and livestock from waste perspective*

The estimated daily manure production based on the number of selected livestock animals is presented in Table 1. Manure refers to livestock waste consisting of animal excreta, with or without litter such as hay, straw, or bedding, that can be used to fertilise land. With its high organic content, livestock manure can also be converted into biogas, a renewable source of energy. Based on published conversion factors, 1 metric ton of manure can produce about 36 m3 of biogas, and 63.8 kWh of electricity can be generated from biogas (Recebli et al., 2015; Khalil et al., 2019). Based on projected livestock populations for 2050, the total daily manure production for the selected livestock animals is estimated at 46,731 × 103 metric tons. This amount of manure could potentially produce 1.69 × 109 m3 of biogas and generate about 2.99 × 109 kWh of electricity, demonstrating the significant resource recovery potential of livestock waste.

Table *1 Estimated value of global daily manure production based on the number of selected livestock animals for the years 1963, 2007 and 2050, including the projected value of potential biogas and electricity production in 2050*

Livestock		Buffalo & Cattle	Goat & Sheep	Pig	Poultry
Daily manure production per head (kg) (Zayadi, 2021)		16.78	1.86	3.36	0.09
1963	Number of animals (million) (Alexandratos & Bruinsma, 2012)	1,045	1,356	424	4,435
	Total daily manure production (metric ton)	$17,535\times10^3$	$2,522\times10^3$	$1,425\times10^3$	399×10^3
2007	Number of animals (million) (Alexandratos & Bruinsma, 2012)	1,532	1,915	917	19,160
	Total daily manure production (metric ton)	$25,707\times10^3$	$3,562\times10^3$	$3,081\times10^3$	$1,724\times10^3$
2050	Number of animals (million) (Alexandratos & Bruinsma, 2012	2,032	2,939	1,141	37,030
	Total daily manure production (metric ton)	$34,097\times10^3$	$5,467\times10^3$	$3,834\times10^3$	$3,333\times10^3$
	Total daily manure production (metric ton)	$46,731\times10^3$			
	Potential biogas production (m^3) (Recebli et al., 2015)	1.69×10^9			
	Potential electricity generation (kWh) (Khalil et al., 2019)	2.99×10^9			

5. Transitioning Towards Sustainable Livestock Practices

Green practice can be described as practices or measures taken which can eliminate, minimise or reduce the negative impacts of human activities on the environment. Ideally, green practice promotes sustainability; the principle of which the current needs are fulfilled without jeopardising the future generations' needs (Szücs, 2009). Besides green practices, there is also green technology. According to the National Green Technology Policy, green technology refers to products, equipment, or systems which minimise environmental damage, emit zero or very little GHG, harmless, conserve energy and natural resources, and encourage the use of renewable resources (KeTTHA, 2009). Recently, there have been concerns regarding food crises at a global scale due to climate change and other reasons, including conflict/war and economic shock after the COVID-19 pandemic (FSIN, 2022; Peterson, 2022). We should look for ways to minimise the climate impact of the livestock sector to ensure sustainable livestock production.

5.1 Waste Management

As livestock productivity increases to fulfil SSL targets and market demand, equal attention must be given to the waste generated by the sector. An increase in livestock numbers means that farms must also increase their capacity for waste management. Fig. 5 presents a proposed waste management hierarchy for livestock waste, adapted from previous studies (Fagariba & Song, 2016; Lewis & Gertsakis, 2024; Menyuka et al., 2020). The hierarchy outlines priority actions that can be taken to avoid or minimise negative environmental impacts. Conventional waste management often emphasised disposal, but the hierarchy places landfill disposal as the least preferred option and prioritises prevention, reduction, reuse, recycling, and recovery (Fagariba & Song, 2016; Menyuka et al., 2020).

In Fig. 5, the inverted pyramid suggests the best ways to manage waste at the top, while the least favourable options are at the bottom. Refusing or preventing waste should be the priority because it avoids waste from being created in the first place. For livestock farms, this means enhancing the diet and digestion of the animals to ensure less manure is produced. Then it is followed by reducing, which means minimising the amount of waste generated. By focusing on prevention and reduction of waste, farms can avoid the need for more complex and costly waste management methods later on. When waste cannot be prevented or reduced, it should be put to a new use. The generated waste can either be reused, recycled, or recovered before being sent for disposal. Here, the key is to handle the waste properly to reduce the amount of waste being disposed of. In livestock farms, the treated wastewater can be reused while the manure can be composted for crop use or recovered as biogas to generate electricity. Finally, at the bottom of the hierarchy is disposal, which should be the last option. This method should only be considered when all other methods are not possible. The waste hierarchy gives livestock farmers the opportunity to reduce pollution, improve sustainability, and create value from waste materials while complying with environmental regulations.

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Livestock manure is packed with nutrients, making it valuable for recycle and recovery process. The nutrient content in livestock manure, including nitrogen (N), phosphorus (P), potassium (K) and other secondary nutrients makes it a good nutrient source for plants (Kumar et al., 2013). Despite the increase in livestock population, the utilisation rate of livestock manure did not rise (Wang et al., 2018). The demand for fertiliser grows each year by 1.8%, however livestock manure makes only a small portion of the fertiliser market with less than 8% of major crop fields utilising the livestock manure (Sadeghpour & Afshar, 2024). Using livestock manure as fertiliser can replenish soil nutrients, improve soil structure, increase water holding capacity, support soil microorganism activity, and reduce the dependency on chemical fertiliser (Aprylasari et al., 2025). Nevertheless, it is advisable to treat livestock manure before using it as fertiliser to avoid water and soil pollution that may be caused from nutrient leaching and pathogen contamination (Kumar et al., 2013; Dadrasnia et al., 2021).

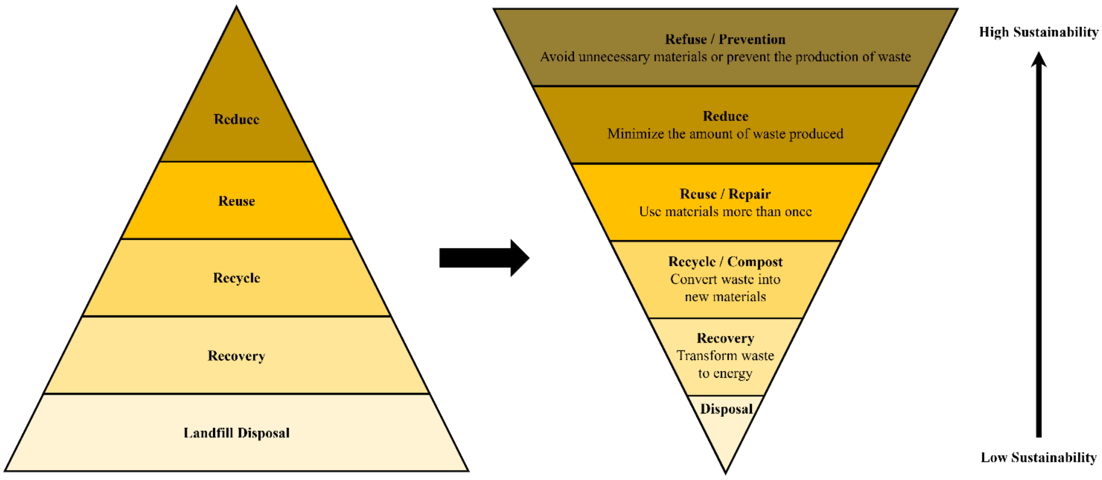

Fig. 5 *Proposed waste management hierarchy for livestock farming*

Waste valorisation is the process of transforming waste materials into valuable products. Livestock waste valorisation to extract nutrients from livestock manure includes anaerobic digestion, composting, and pyrolysis (Dixit & Bardiya, 2025; Márquez-Moreno et al., 2026). Anaerobic digestion is the decomposition of livestock waste in oxygen-free conditions to produce biogas and a nutrient-rich by-product called digestate (Márquez-Moreno et al., 2026). Composting is the decomposition of livestock waste by aerobic microorganisms to produce stabilised organic matter (compost). It can be done either through static piles, windrow piles or using vessels (Boboua et al., 2024). Vermicomposting which uses earthworms to accelerate the decomposition can also be done to produce organic fertiliser from livestock manure (Vasmara & Martini, 2025). Meanwhile, pyrolysis is a thermochemical process done in the absence of oxygen at 300 – 900 °C which converts the manure into biochar to enhance soil properties (Dixit & Bardiya, 2025; Márquez-Moreno et al., 2026). Rendering is another technique for waste valorisation that separates protein and fat from livestock waste, and further used as industrial, agricultural, and pharmaceutical materials (Boboua et al., 2024; Vasmara & Martini, 2025).

Besides the solid waste, another concern with livestock waste is the emission of GHG. Livestock emits GHG such as methane (CH4) from enteric fermentation, as well as methane and nitrous oxide (N2O) from manure management. Methane is released from enteric fermentation due to ruminant eructation, whereas methane from manure results from bacteria breaking down organic materials under anaerobic conditions (Nugrahaeningtyas et al., 2024). The production of a kilogram of beef emits 23.4 – 27.2 kg CO2-eq of GHG, while lamb production emits 6.1 kg CO2-eq GHG per kilogram of lamb (González et al., 2020). The released GHG will trap heat in the atmosphere and is responsible for climate change through the occurrence of extreme weather events such as droughts and floods (Zaman et al., 2021). Sustainable manure management is therefore crucial to reduce the emission of GHG to the atmosphere.

Livestock manure can be harnessed and converted into biogas. Biogas is a gaseous fuel, mainly composed of methane and smaller amounts of carbon dioxide (CO_2), hydrogen sulphide (H_2S) and trace gases which can be utilised for electricity generation, transportation fuel, cooking, and heat generation for consumer use and plant operation (Sadeghpour & Afshar, 2024; Richards & Yabar, 2023). Typically, biogas from livestock manure is produced by anaerobic digestion in bioreactors or biodigesters where several parameters are controlled, such as temperature, pH, macro- and micronutrients, organic loading rates, microbes, and humidity content (Matheri et al., 2024). Anaerobic digestion produces biogas (composed of 50-70% CH_4, 30-50% CO_2 and traces of H_2S) along with nutrient-rich digestate that can serve as organic fertiliser (Dixit & Bardiya, 2025).

Effective management of livestock waste following the proposed waste hierarchy is essential for achieving a balance between livestock production growth and environmental sustainability. Prioritising waste prevention is an essential effort towards the adoption of green practices in livestock management. For unavoidable waste, efficient waste valorisation methods such as composting and anaerobic digestion can transform the livestock waste into organic fertiliser and biogas, therefore mitigating environmental impacts and promoting renewable energy generation. Waste valorisation of livestock manure presents a dual opportunity to manage livestock waste sustainably and to recover or transform the nutrients into other useful products.

5.2 Water Management

Water management in the livestock sector involves both water consumption and wastewater production. In global animal production, water is largely used for feed production, while only about 2% is used for drinking and servicing activities such as washing, cleaning, and disinfecting farms (Heinke et al., 2020; Mekonnen & Hoekstra, 2012; Krauß et al., 2016). Annually, the livestock sector uses about 11,900 km3 of freshwater, where 20% of blue water is used for feed production (FAO, 2019). The average drinking water consumed by beef cattle and dairy cattle is 38 L/head/day and 70 L/head/day, respectively, while the average water used for farm operations is 11 L/head/day and 22 L/head/day, respectively (Kılıç et al., 2023).

Farmers may not be able to control the water used for feed production, but they can use water efficiently in the farms. Recommended measures for efficient water use in the farms include using constant-level drinkers instead of valve drinkers, using high-pressure washing equipment, and improving building design to reduce overheating and excessive water intake by animals (Monteiro, 2023). A rainwater harvesting system can also be adopted to reduce dependence on freshwater use for livestock farms. A study found that farms using harvested rainwater for drinking water and farm operations reduced their annual average water costs by half and conserved a significant amount of water (Kılıç et al., 2023).

Livestock wastewater is the mixture of animal excreta with processing water used in the maintenance of livestock on the farm. Annually, over 24 billion tonnes of livestock wastewater are generated, containing high levels of organic pollutants and often discharged into the environment without proper management (Silva-Gálvez et al., 2024). Previous research concluded that ¼ of the global sub-basins are pollution hotspots due to high levels of N, P and Cryptosporidium (pathogen), resulting from intensive livestock farming and direct manure discharge into rivers (Li et al., 2022b). Livestock wastewater may contain organic compounds like nutrients, pathogens, drug residue, and hormones, as well as inorganic compounds such as heavy metals (FAO, 2018). Therefore, proper treatment of livestock wastewater should be implemented to prevent environmental pollution.

Fig. 6 illustrates a typical livestock wastewater treatment system and shows how wastewater can be separated, stabilised, treated, and reused before final discharge. Since livestock wastewater contains a high amount of organic matter, the use of a solid separator is advisable to enable more efficient nutrient recovery through available waste valorisation techniques. The separated wastewater has a lower suspended-solids load and is therefore easier to treat before being discharged or recycled. The estimated wastewater generated from rearing a cow is approximately 100-150 L/day for cattle weighing 400 kg (Chandrasasi et al., 2021). Dairy wastewater may have biological oxygen demand (BOD) of 40,000-48,000 mg/L, chemical oxygen demand (COD) of 10,000-50,000 mg/L, and total suspended solids (TSS) of 2.8 mg/L (FAO, 2025a). These nutrients should be recovered through an appropriate treatment system so that they do not overwhelm the receiving environment.

The first stage of livestock wastewater treatment involves using a solid separator. Solid-liquid separation is an affordable treatment option that separates solids from the wastewater to produce a liquid fraction and a solid fraction of dry matter rich in nutrients, which can be further managed separately (Cocolo et al., 2012). The solid fraction is rich in organic N and P, while the liquid fraction has low P, but high N and K content (FAO, 2025a). The solid separator usually operates by gravity filtration (inclined screen, vibrating screen or rotating screen), pressurised filtration (screw press, roller press or belt press), centrifugation, or a combination of these methods to separate the solid and liquid fractions from livestock wastewater (Cocolo et al., 2012; Burns, 2022). Solid separator as the first treatment step is economically beneficial because the separated solid can be processed and transported effectively (Grell et al., 2023). The separated solid which is rich in nutrients can be managed sustainably using manure treatments such as composting or anaerobic digestion to generate valuable products rather than being disposed of.

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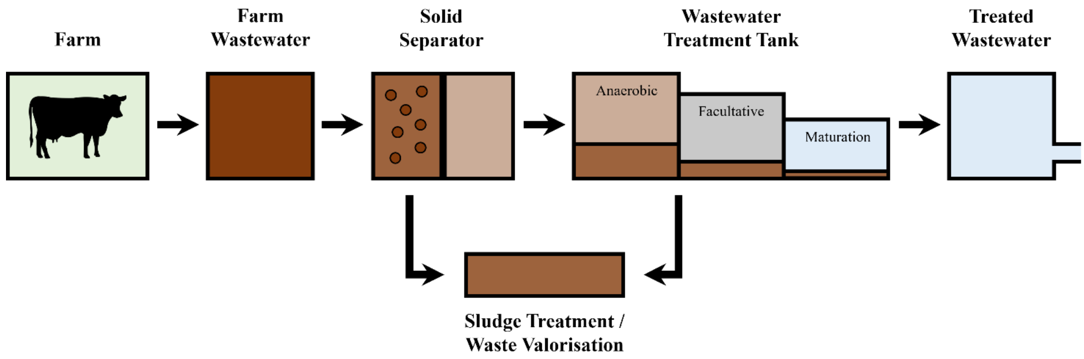

Fig. 6 *Typical water treatment for livestock wastewater*

Following the solid separator, settling lagoons or waste stabilisation ponds (WSP) can be used to contain livestock wastewater or the separated liquid fraction for an amount of time to reduce its sludge load. This is important to avoid the risk of wastewater polluting surface and groundwater, as pollutants such as heavy metals are present (FAO, 2025a). Lagoon systems consist of one or more ponds that treat livestock wastewater for a designated time, lined with clay or synthetic material to prevent leakage into the soil and water sources (Miller et al., 2011). It is recommended that livestock farms have a series of WSP to ensure the wastewater meets the discharge limit (DVS, 2019). Common types of WSPs in livestock farms include anaerobic ponds, facultative ponds, aerobic maturation ponds, and aerated ponds (DVS, 2019; Verbyla et al., 2017). The typical arrangement is first anaerobic pond (≥3.0 m deep), followed by facultative pond (1.5 – 3.0 m deep), then aerobic maturation pond (≤1.5 m) (Verbyla et al., 2017). The anaerobic pond removes 50-70% of BOD, and causes the wastewater to separate into layers with heavy sludge at the bottom while a top layer seals out oxygen to create the anaerobic conditions for bacteria to treat the wastewater (Miller et al., 2011; DVS, 2019). In facultative pond, the odour emission is minimised with an aerobic zone at the top where the wastewater is exposed to oxygen, while the bottom layer is an anaerobic zone where the wastewater is stabilised anaerobically (Miller et al., 2011). Maturation pond is the shallowest to allow light penetration and provide aerobic conditions throughout the pond, plus it also removes pathogens through oxidation process (Menya et al., 2013).

Treated livestock wastewater should follow local regulations prior to being discharged. Besides that, the treated effluent can also be recycled for use in agriculture and aquaculture (Menya et al., 2013). It can be used as water for crop irrigation since it provides nutritional inputs for crop growth (Miller et al., 2011; Giang et al., 2021). A research found that livestock wastewater used for irrigation had improved the soil components, particularly nitrate nitrogen, phosphorus, and humus (Mukhametov et al., 2022). It is advisable to use it for irrigation of crops that are not for fresh consumption such as wooden trees, or use it for pasture irrigation. Using treated livestock wastewater for irrigation of fresh food crops such as fruits and vegetables may pose a risk due to the content of coliform (Giang et al., 2021). While recycling livestock wastewater for crop irrigation promotes zero waste, careful consideration should be given as wastewater from certain livestock such as swine may be a sensitive issue to some people.

Proper treatment of livestock wastewater is critical for sustainable agricultural practices and environmental protection. Separating the solid and liquid components of livestock wastewater is a simple preliminary step that allows effective wastewater treatment. Using waste stabilisation ponds can enhance water quality and help to achieve the discharge limit to safeguard public health and the environment. Nutrients from livestock wastewater can be recovered from the treatment system and be further treated following the waste valorisation techniques, or being recycled for crop irrigation. Ensuring that livestock wastewater is properly treated before recycling or reuse is also essential to prevent any health risks.

Aside from the aforementioned strategies, livestock farms should also adopt Good Animal Husbandry Practices (GAHP). The implementation of GAHP covers the aspects of animal welfare, food safety and environmental sustainability through sanitary and humane farming practices (Suharni et al., 2021). Malaysian Good Agricultural Practices (MyGAP) guideline which was constructed based on GAHP highlights the component of animal health programme (to ensure proper animal health monitoring and control), biosecurity programme (to prevent the entry of disease-carrying agents into the farm), premise and infrastructure (to provide appropriate farm layout and infrastructure for operation), use of medication (to ensure controlled use of medication to avoid drug residue), and waste management and pollution control programme (to ensure the livestock waste is properly managed to avoid pollution) (MOA, 2013). At this moment, the adoption of GAHP is voluntary. However, implementing GAHP should be promoted as it supports sustainable livestock production.

6. Circular Economy Approach for Sustainable Livestock Production

According to the Food and Agriculture Organization (FAO), a circular economy is a system that minimises waste materials and promotes the regeneration of nature (FAO, 2025a). The circular economy model supports a transition from a linear structure of "take-make-dispose" to a circular approach of "use-make-return" to minimise energy consumption, conserve natural resources, and reduce waste generation (Matheri et al., 2024). It was envisioned as a way to keep the planet sustainable given the limited resources available on Earth (Ramirez et al., 2021). Compared with the traditional linear economy, where products and materials are discarded after use, the circular economy keeps materials in circulation through processes such as maintenance, reuse, repair, refurbishment, and recycling. Fig. 7 contrasts the linear economy, recycling economy, and circular economy models to show how value can be retained for a longer period. In a circular economy, the amount of waste generated is reduced because the value and function of products are maintained over time, and when products reach the end of their life, their functions can be renewed through recycling or recovery.

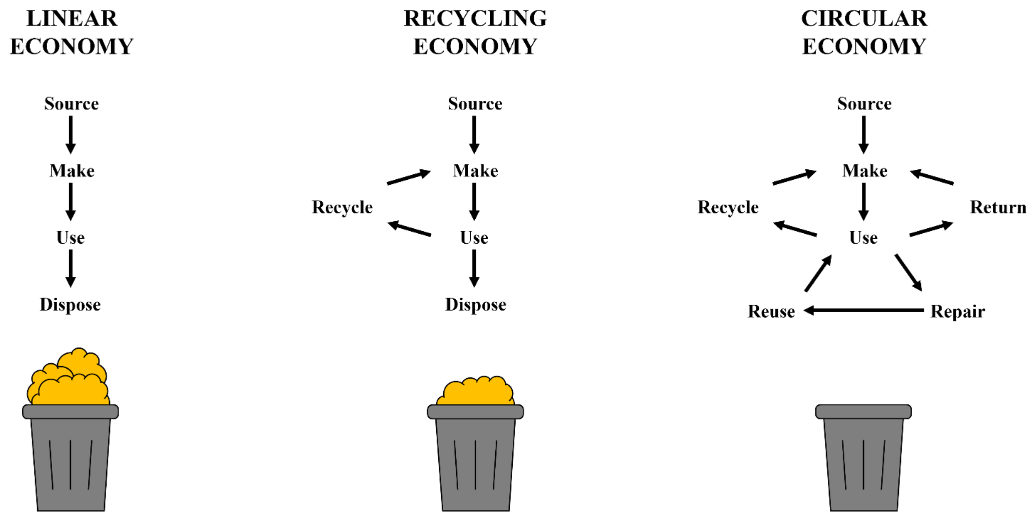

Fig. 7 *Difference between linear economy, recycling economy and circular economy*

Circular economy practices in livestock farming are not entirely new; farmers may have adopted them to reduce production costs even before the term became widely used. Fig. 8 summarises common practices that support circular economy in livestock production. Within crop-livestock interactions, these practices include using livestock manure as compost or organic fertiliser for crops, using crop waste or biomass as livestock feed, and integrating crop and livestock production on the same land. Within livestock-consumer interactions, circular practices include converting livestock manure into biogas or compost, using post-processing livestock waste for downstream products, and using food waste as livestock feed.

According to a publication by Malaysia Productivity Corporation (MPC), circular economy in livestock production can be implemented at macro-level, meso-level, and micro-level (MPC, 2020). At macro-level, the adoption of circular economy occurs seamlessly along the production value chain which may involves crop farming, livestock farming, processing plants, and the consumers. At the meso-level, the adoption of circular economy occurs when wastes or by-products from an industrial process become the raw materials for another industry such as the crop biomass utilised as feed for livestock. At the micro-level, it can be seen from the integrated crop-livestock system.

The recycling or reuse of livestock manure either for use as compost and organic fertiliser or converted into biogas gives benefits to the environment and the industry. From environmental perspective, the treatment of manure will stabilise the waste, reduce pathogens and odours, as well as reduce the dependency on synthetic chemical fertilisers (Aprylasari et al., 2025; Ramirez et al., 2021). From circular economy perspective, the biogas generated from the manure can generate heat or electricity that can be used at the premise to offset the heating and electricity requirements (Ramirez et al., 2021). Integrated crop-livestock farming system such as oil palm and cattle integration also illustrates the benefits of circular economy in livestock production. The crops can utilise livestock waste as organic matter to enhance the surrounding soil, and at the same time the livestock gets feed from crop residues, crop by-products, or grazing on weeds under the trees (Patel et al., 2015; Swastika et al., 2024). When cattle graze on the oil palm, it helps control weeds which reduces the cost of weed management and minimises the impact of using herbicide to the ecosystem (Umar et al., 2023).

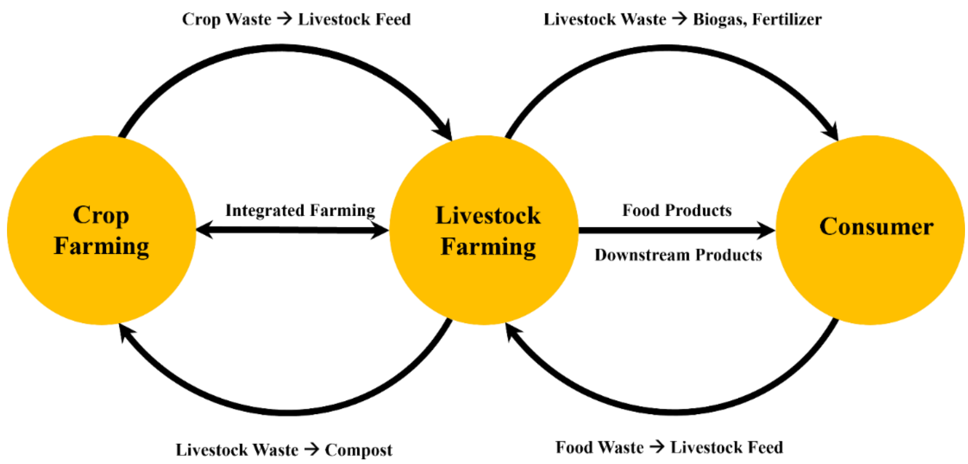

Fig. 8 *Common practices of circular economy in livestock production*

Circular economy practices in the livestock sector support several Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Converting inedible biomass such as crop residues into livestock feed contributes to SDG 2, while using livestock waste to improve soil fertility and replace synthetic fertiliser contributes to SDG 12. Reducing GHG emissions through nutrient recycling and waste-to-energy systems supports SDG 13 (FAO, 2025a). Previous research found that a 62% reduction in environmental impact from an integrated livestock system favouring circular economy practices can be achieved, with 30-56% of nutrients needed for crops supplied by livestock waste (Taifouris & Martin, 2021). Adopting circular economy practices in livestock production therefore provides synergistic benefits across integrated industries, food systems, and the environment.

7. Conclusion

The livestock sector plays an important role in global food systems by providing essential nutrients and contributing to food security. However, the sector also faces interconnected sustainability challenges, including resource depletion, waste generation, water pollution, public health risks, and GHG emissions. This review shows that sustainable livestock production requires a shift from a linear production model towards green practices and circular economy approaches. The formal review and secondary data analysis indicate that increasing population and livestock demand will intensify manure and wastewater generation, but these by-products can be transformed into valuable resources through waste hierarchy practices, manure valorisation, anaerobic digestion, composting, wastewater treatment, water conservation, and resource recovery. The projected potential for biogas and electricity generation from livestock manure demonstrates that waste can be managed not only as an environmental burden but also as a renewable resource. Therefore, adopting sustainable livestock practices is essential for balancing food production, environmental protection, and long-term resource security.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, literature review, data collection, analysis and interpretation of results, and manuscript preparation.

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