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Greenhouse Gas Emissions from Livestock Operations - Mitigation Options in the African Tropics for Sheep and Goats

By

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Abstract

This study evaluates methane emission trends in livestock production and explores potential mitigation strategies, including feed manipulation and microbial interventions. Methane forms about 44 % of livestock emissions. The rest is shared between Carbon dioxide (27%) and Nitrous oxide (29%). Cattle emit the highest, about 65 % of the livestock production emissions. Feed processing, production, and enteric fermentation from ruminants are the two major sources of emissions, contributing 45 % and 39 % of total emissions respectively. Methane emitted from ruminant livestock is regarded as a loss of feed energy and a contributor to global warming. Methane is synthesized in the rumen as one of the hydrogen sink products that are unavoidable for efficient succession of anaerobic microbial fermentation. Various attempts have been made to reduce methane emission, mainly through rumen microbial manipulation, using agents including chemicals, antibiotics, and natural products such as oils, fatty acids, and plant extracts. A newer approach is the development of vaccines against methanogenic bacteria. Manure storage and processing forms 10 % and the rest is attributed to transportation and animal processing. On product-basis, milk from cows and beef are responsible for the most emissions, contributing 20% and 41% of the sector's total greenhouse gas (GHG) outputs respectively. Storage of manure and supply of feed form the bulk of emissions in pig production while supply of feed forms the bulk in poultry. Optimized feeding strategies and microbial interventions are examples of targeted mitigation strategies that can improve sustainability by lowering emissions associated with livestock production. It is concluded that the targeted mitigation strategies are critical for livestock methane emissions as they contribute to greenhouse gases. Optimized feeding, microbial interventions, and selective breeding can enhance sustainability. Meeting these challenges will sustain livestock productivity with a decreased environmental impact.

Keywords: *Enteric fermentation, Livestock greenhouse gases, Methane emissions, Methane reduction strategies, Rumen microbial manipulation*

Introduction

Livestock contributes both directly and indirectly to climate change through the emissions of GHGs such as carbon dioxide (CO_2), methane (CH_4), and Nitrous oxide (N_2O) (Bhatta *et al.*, 2015). Globally, the sector contributes 18% (7.1 billion tonnes CO_2 equivalent) of global GHG emissions (FAO, 2006). Although it accounts for only 9% of global CO_2, it generates 65% of human-related N_2O and 35% of CH_4, which has 310 times and 23 times the global warming potential (GWP) of CO_2, respectively (FAO, 2008).

The main reasons for high emissions intensities in African livestock systems are low productivity and low feed digestibility. If livestock uses energy to maintain body weight and basic functions, rather than producing meat or milk, the GHG emissions intensities per kg of 'product' are very high. If productivity increases, emissions per unit of animal product will decrease (even if overall methane increases) and ultimately producers should be able to keep fewer, more productive animals (Ericksen and Crane, 2018).

In Africa, although total emissions from livestock are still lower than in the member states of the Organization for

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Economic Cooperation and Development (OECD), the emissions intensities per unit of animal product produced are very high (Herrero *et al.* 2013), which is a cause for concern given the rapid growth projected for the sector. Kenya and Ethiopia both have economically important livestock sectors. In Kenya, the livestock sector contributes about 12% to GDP and 40% to agricultural GDP (IGAD LPI 2011). Kenya has one of the largest dairy sectors in sub-Saharan Africa, contributing 8% of GDP (Odero-Waitituh 2017). In Ethiopia, although the dairy sector is not well developed, livestock production contributes between 25 and 45% of agricultural GDP (Behnke 2011), with a live animal trade valued at over USD 45M in 2008 (Aklilu *et al.* 2013). However, inefficient production systems lead to GHG high emissions intensity, measured as the amount of GHG per unit of product (meat, milk, calories, protein). The livestock sectors in both countries face feed shortages, and a lack of investment in improved genetics, animal health services, and farm inputs.

Methane emission takes place from both enteric fermentation and manure management while nitrous oxide emission is purely from manure management. Rumen methanogenesis due to emission intensity and loss of biological energy always remains a priority for researchers. Greenhouse gas (GHG) emissions from manure are determined by storage conditions and the organic content of the manure waste.

Methane (CH_4) is the second most prevalent greenhouse gas (GHG) after carbon dioxide (CO_2) with a global warming potential (GWP) of 20 to 23 greater than CO2 over 100 years (Steinfeld *et al.*, 2006). Methane has a lifetime of about 9 to 15 years in the atmosphere (Yan *et al.*, 2010). Globally, 6,875 million metric tons of CO_2 equivalent ($MMTCO_2$ eq.) of methane are released annually from anthropogenic sources, half of which is from agricultural sources and mainly from ruminants, manure management, biomass burning, and rice cultivation (EPA, 2008; Tubiello *et al.*, 2013; Haque *et al.*, 2014). In ruminant production systems, enteric CH4 production is the largest contributor to GGE followed by CH4 from manure systems, main emission sources are enteric fermentation, feed fertilization, and land application (Hristov *et al.*, 2013; Montes *et al.*, 2013). The digestibility of ingested plant biomass, which is determined by the ratio of insoluble cell wall fibre to soluble carbohydrates, directs enteric fermentation to the preferential production of certain end products (Migwi *et al*., 2013).

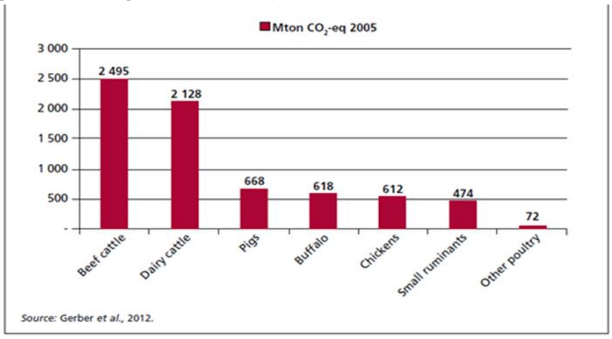

Figure 1: Total emissions from the global livestock sector by main animal species and commodities.
Source: Gerber et al., 2012

Methane production appears to be a major issue and largely arises from natural anaerobic ecosystems, and fermentative digestion in ruminant animals (Sejian *et al.*, 2012b). Much of the global GHG emissions currently arise from enteric fermentation and manure from grazing animals. The development of management strategies to mitigate CH_4 emissions from ruminant livestock is possible and desirable. Carbon dioxide (CO_2) is also produced in livestock farms and is primarily associated with fossil fuel burning during the operation of farm machinery in the process of fertilizer production, processing and transportation of refrigerated products, deforestation, desertification, and release of carbon from cultivated soils.

The final products of enteric fermentation include acetate, formate, methanol, carbon monoxide, carbon dioxide, and hydrogen gas, all of which are substrates for methanogenesis (Moss *et al.*, 2000; Merino *et al*., 2011). It was found that 89 % of gases are excreted through the breath and only 11 % through the anus (Madsen *et al*., 2010).

Enteric methane emission

Enteric fermentation is a natural part of the digestive process in ruminant animals such as cattle, sheep, goats, and buffalo. Approximately 80% of the anthropogenic methane emissions are derived from ruminant production, especially in extensive production systems (Gill *et al.*, 2010). Among the ruminants, the cattle population contributes most towards enteric CH4 production (Zijderveld van *et al.*, 2011; Sejian and Naqvi, 2012a).

The rumen has a microbial population highly capable of fermenting dietary carbohydrates, Among the microbial groups, species of bacteria, protozoa, fungi, and, with a population ranging from 0.5 to 3.0%, are the organisms of the domain *Archae*, also known as methanogenic bacteria (Hackmann & Spain, 2010).

The ingested foods are anaerobically fermented and converted into short-chain fatty acids (SCFA), mainly acetate, propionate, and butyrate, branched-chain fatty acids, microbial protein, vitamins from the K and B complex and gases from the fermentation process, such as carbon dioxide (CO2), nitrous oxide (N2O), hydrogen (H2) and methane (CH4) (Sejian *et al.*, 2017). Through flatulence and, mainly, eructation, CH4 is eliminated from the ruminal environment and such activities are natural consequences of preventing gas accumulation (Muñoz, Yan, Wills, Murray, & Gordon, 2012).

Factors affecting enteric methane production

Environmental temperature

The temperature of the environment has a great impact on the production and rate of enteric methane (CH_4). An increase in temperature often leads to a decrease in feed intake. As feed is ingested, there is a passive reduction in the rate of feed passage within the digestive tract. This leads to a rise in the digestibility of the feed. Because of this, the loss of energy in the form of CH_4 may be minimized. On the other hand, sustained high-temperature conditions tend to increase the circulating temperature above that which is considered normal, altering the feed composition by increasing the concentration of structural carbohydrates such as acid detergent fiber and lignin which makes the feed less digestible and less usable for energy. Thus, the efficiency of animal production deteriorates leading to an increase in the CH_4 emission per unit of production (Beltrani *et al.*, 2023).

In these instances, the impacts felt are extremely severe from a geographical standpoint in the tropics, as these regions will permanently be faced with high-temperature challenges (Shibata and Terada, 2010). However, these trends are being seen in and around temperate regions as well. With the progression of climate change, these areas will also witness an increase in livestock CH_4 emissions. Other studies have suggested that there is a degree of heat stress that could also make these far more difficult to cope with, thus negative impacts on feed efficiency and rising emission of methane gas are bound to occur (Feyissa *et al.*, 2023).

Feeding

The kind and amount of feed consumed are the major driving factors of enteric methane emissions (Arias *et al.*, 2015). Compared to intensive feeding systems, extensively managed grass-based systems seem to yield greater daily CH_4 emissions (Sejian and Naqvi, 2012a). This is mainly due to a diet's greater fiber concentration, which increases methane-producing fermentation in the rumen.

Methane has been observed to be influenced greatly by diet composition. Ricci *et al.* (2014) observed an increase in methane emissions for finishing steers under a low-concentrate ration in comparison to those on high-concentrate rations. The same observation was made by Jiao *et al.* (2014), where dairy cows that were fed concentrates in addition to grass had not only increased milk production but also lower CH_4 emissions per unit of milk produced.

In the recent past, there has been some research done on the nutritional approaches to reducing methane emissions, adding lipids, tannins, and essential oils to livestock diets being some of the proposed options. These supplements have been shown to reduce methanogenesis by changing the demographic structure of the rumen microorganisms by inhibiting methane producing archaea (Beltrani *et al.*, 2023).

Internal and Genetic Factors

The differences in enteric methane emissions occur within individual animals, breeds, and over time, which indicates that there is an opportunity for genetic selection to enhance productivity (Haas de *et al.*, 2011). There are also significant differences in CH_4 production between species and breeds; for example, heifers emit approximately about 7 times and 9 times as much as sheep and goats, respectively (Pedreira *et al.*, 2009).

One of the innovative approaches in livestock management is genetic selection for methane-emitting animals that are less productive. Some breed differences have been linked to lower emissions of methane because of the microbiota in the rumen and their efficiency in converting feed. There are ongoing efforts to genomic selection and breeding systems to mark and multiply animals with favorable traits for lower emissions of methane (Feyissa *et al.*, 2023).

Enteric Fermentation Emissions from Sheep

The GHG emissions associated with sheep production include enteric CH4 emissions, manure and bedding emissions, and emissions associated with grazing and manure application to land.

The main sheep-producing countries, concentrated in Oceania and Western Europe, are contributing the least amount of enteric CH4 emissions, compared to goat-producing countries in developing areas. This is due to the greater intensification of production in developed countries, and the model of subsistence in emerging regions (Salem, 2010). Greater prolificacy, leading to a greater number of lambs born per lambing cycle, and short cycles to produce meat contribute to the efficiency of the system (Marino *et al.* (2016).

The New Zealand Ministry for the Environment (2010) estimated that sheep younger than a year of age emit 5.1 percent of GEI as enteric CH4 and adult sheep emit 6.3 percent of their GEI as CH4. These emission factors, when combined with population estimates, result in baseline enteric emissions of 11.60 kg CH4 head-1 year-1. Sheep are also estimated to deposit 15.9 kg N head-1 year-1 (Powers *et al.*, 2014). Lassey (2007) summarized the enteric emissions measurements from grazing sheep trials from New Zealand and Australia in which the SF6 tracer technique was used. Forage characteristics ranged from lush (in vitro digestibility estimate of 82 percent) to poor quality (called "dead," with an *in vitro* digestibility of 54 percent). Intake was measured using complete fecal collection or a marker (n-alkane). Enteric CH4 emissions ranged from 11.7 g day-1 for sheep-fed forage of higher quality (6.9 percent of GEI) to 35.2 g day-1 for sheep-fed forage of lower quality (6.3 percent of GEI). The average enteric emissions were 5.39 percent of GEI or 23.5 g day^{-1}. In general, lower forage quality resulted in a greater amount of CH4 emitted as a proportion of the energy intake than did higher forage quality. New Zealand pastures grazed by sheep had elevated N2O emissions (7.4 g N2O-N ha-1 day-1 vs. 3.4g N2O-N ha-1 day-1) compared with control, but significantly less than that observed when cattle grazed (32.0 g N2O-N ha-1 day-1) (Saggar *et al.*, 2007). The data were used to evaluate the NZ-DNDC model, a process-based New Zealand whole-farm model. To our knowledge, there are no published estimates of GHG emissions from sheep manure systems.

Enteric emissions from goats

Morphologically versatile goat species with unique browsing potential adapt to a changing climate more readily than other ruminant species and consequently, they continue to be an important source of income and nutrition to many poor and marginal farmers around the world (Feleke *et al.*, 2016). Goats are also the major means of employment and income for women, children, and aged people in tropical and

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subtropical regions (Bezabih and Berhane, 2014). The important sources of income from the sector include milk, meat, manure, wool, and skin (Thornton, 2010). Small ruminants, and in particular goat, are very important because of the relatively low input requirements and the corresponding high expected output (Brahmi *et al.*, 2012). Furthermore, goats emit less enteric methane (CH4) than all other domestic ruminant animals per unit body weight (Koluman *et al.*, 2017).

Small ruminants, in particular goats, are considered an important source of income and nutrition for poor and marginal farmers around the world (Koluman *et al.*, 2017). Low initial investment and high turnover rate for goat production are the primary reasons behind the promotion of the goat industry in developing countries (Pollot and Wilson, 2009). Goats are often referred to as village banks in some rural areas where the villagers invest their money in purchasing and feeding goats and consider it as an appropriate way to save money for the future (Oluwatayo and Oluwatayo, 2012). Globally, there are estimated to be over 860 million goats (Aziz, 2010) and recent trends show an increased demand for dairy products from goats, particularly in developing countries where they act as a substitute for dairy products from large ruminants for human dietary needs (Lérias *et al.*, 2014). Goats are versatile animals that adapt to a changing climate more readily than other ruminant species and are well-suited to small farming systems (Feleke *et al*., 2016).

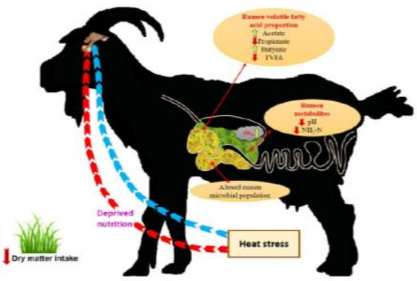

Figure 2: Impact of heat stress on various rumen functions of goats

Source: Pragna *et al.*, 2018

Livestock manure is an important source of GHGs

In addition to enteric CH_4 production, livestock manure contributes directly and indirectly to GHG gas production via CH_4, N_2O, and CO_2 production. Manure from livestock includes both dung and urine. Livestock manure is primarily composed of organic material and water. Anaerobic bacteria decompose the organic material under anaerobic conditions, releasing CH_4 (EPA 1999). Methane emissions from manure management are mostly associated with confined animals where manure is managed under different management systems (IPCC 2006; Baggot *et al.*, 2006).

The quantity of CH_4 emitted from manure management operations is a function of three primary factors: (1) the manure management system, (2) the environmental conditions, and (3) the amount and composition of the manure (EPA 2010). The management system determines key factors that affect CH_4 production including contact with oxygen, water content, pH, and nutrient availability. When manure is stored or treated as a liquid in a lagoon, pond, or tank it tends to decompose anaerobically and produce a significant quantity of CH_4. In contrast, when manure is handled as a solid or deposited on pastures it tends to decompose aerobically, and little or no CH_4 is produced (IPCC 2006).

Factors affecting methane production from manure

Several factors affect the CH_4 production from manure, which includes temperature, organic matter present, microbe load, pH, moisture, and type of feed. However, CH_4 emitted from manure depends primarily on (i) the management system such as solid disposal system, liquid disposal systems, e.g., ponds, lagoons, and tanks, which can emit up to 80% of manure-based CH_4 emissions, while solid manure emits little or no CH_4. (ii) Environmental conditions are also important. The higher the temperature and moisture, the more CH_4 is produced. (iii) CH_4 emissions also depend on the quantity of the manure produced, which depends on the number of animals housed, the amount of feed consumed, and the digestibility of the feed. (iv) Manure characteristics depend on the animal type, feed quality, and rumen microbes present in the rumen and digestive tract. Manure handled in liquid form tends to release more amount of CH_4 when compared to solid or manures thrown into the pasture, which do not decompose anaerobically. High temperatures with neutral pH and high moisture content enhance CH_4 production (Bull *et al.*, 2005).

Strategies for Mitigating Greenhouse Gas Emissions

Agriculture accounts for 15% of global emissions of greenhouse gases (GHGs), which include methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). Livestock methane emissions, manure methane emissions, fertilizer usage, and fossil fuel energy consumption while farming all add to this problem. Ranchers and farmers, however, have economically viable options that would allow emission reductions without compromising productivity or sustainability.

The best available option to lower GHG emissions from agriculture is to increase animal productivity, which refers to the output of meat, milk, and other animal products. Feeding practices as well as genetic selection of the animals play a crucial role. Livestock productivity can also be improved with better diets, which in this case means providing them with more digestible feeds. A more favorable feed ratio increases nutrient capture and accelerates digestion in the rumen. It's important to emphasize that a longer retention time in the rumen means more carbon is turned into methane, one of the strongest greenhouse gases. Supporting evidence suggests that greater diet digestibility correlates with lower methane emissions from enteric fermentation methane emissions in livestock and ruminants (Singh *et al.*, 2023).

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Also, for the "optimization" of methane emissions, dietary supplements and additives are of great importance. For example, some edible oils enhance feed efficiency and reduce methane emissions. Some of the feed additives like ionophores reduce methane through their effects on methane-producing flora of the rumen. These efforts, along with improving livestock performance, enable productive and efficient agricultural systems (Kabato *et al.,* 2025).

Selective breeding is another pillar of methods developed to lower GHG emissions. The ability to raise high genetic merit livestock translates to improved feed efficiency, enhanced intake, better fertility, and overall herd health. The genetic enhancement of certain livestock results in a reduced maintenance and production feeding cost, which leads to a lower methane emission per unit of production. Improved reproductive performance plus lower calf mortality also helps reduce emissions because the healthier animals need less resources to grow and mature (Zaman *et al.*, 2021).

One other critical area where emissions may be controlled is in the management of manure. Methane and nitrous oxide emissions are mitigated with proper manure storage and handling. One approach is aerobic processes like composting or aerobic waste treatment systems. These methods prevent anaerobic decomposition of manure which is responsible for methane emissions. Additionally, the recycling of biogas methane enables the conversion of waste into renewable energy as opposed to fossil fuels (Singh *et al.,* 2023).

With improved livestock diets and the use of nitrification inhibitors, the emission of nitrous oxide can also be managed. The fertilization of the soil is the leading activity that generates nitrous oxide emissions. With the use of nitrification inhibitors, the process of ammonium conversion to nitrate which is released into the atmosphere as N2O is hindered. Furthermore, the more modern strategies of manure application like precision spreading and incorporation into the soil improve emissions as well as increase soil fertility (Kabato *et al.,* 2025).

Effective management of pastures aids in decreasing emissions associated with agriculture. Improving pastures increases herds' diets and, thus, methane emissions. Integration of trees into pasture systems, agroforestry also qualifies as pasture improvement and helps in carbon dioxide capture while improving biodiversity. Furthermore, agroforestry with trees directly reduces CO2 emissions associated with livestock emissions and soil management emissions (Singh *et al.,* 2023).

Biogas production via anaerobic digestion is another innovative solution for the reduction of GHG emissions in agriculture. The application of anaerobic digestion technology, which transforms organic waste into energy, enables farmers to produce on-farm energy with organic waste. This shifts the source of energy to a renewable one for farming operations while decreasing methane emissions. Alongside these benefits, precision farming emission reduction and resource use efficiency as optimized management are based on collected data. (Zaman *et al.,* 2021).

Management of manure to reduce greenhouse gas emissions

Manure management plays a key role in the amount of CH_4 and N_2O produced and liberated into the environment. The amount of CH_4 produced in solid-state manure management contribute less when compared to liquid state. However, dry anaerobic management system provides suitable environment for N_2O production. The liquid/slurry manure systems provide favorable environments for the growth of the microbes, which in turn enhances the CH_4 gas production.

Chadwick *et al.* (2011) reported that for nitrous oxide emissions to be reduced from the 1 to 10% lost in stored heaps; anaerobic (i.e. without oxygen) conditions must be maintained. Total methane emissions from manure can be reduced by up to 90% if the heaps are kept covered with an airtight cover or if they are frequently turned to aerate. Various factors that affect CH_4 and N_2O production include the amount of manure, the VFA present, the type of feed, the management systems, and the ambient temperature. In addition, the duration of the storage of waste also influences N_2O production. Nitrous oxide is produced directly and indirectly during the storage and treatment of manure and urine. Direct emissions occur through the processes of nitrification and denitrification while indirect emissions occur through volatilization, leaching, and runoff (Olander *et al*., 2013).

Production and emission of N_2O from manure depend on the digestibility and composition of animal feed, manure management practices, duration of waste management, and environmental conditions. High N_2O emissions are related to a high intake of feed with high nitrogen concentration. N_2O emissions depend on the amount of oxygen and moisture level of the managed manure (IPCC, 2006). Manure stored for long periods results in relatively high emissions of N_2O. The environmental conditions that favor the development of N_2O in managed manure are low pH, high temperature, increased aeration, and low moisture (IPCC, 2006).

Figure 3 provides an overview of the connections between feed, animals, manure, and GHG emissions in an animal production system. At the top of the conceptual model, livestock are fed a variety of diets. Ruminant animals eat feedstuffs and, through fermentation by the ruminal microbes, CH4 is produced. Poultry and swine, although they do not release a significant amount of CH4 through enteric fermentation, deposit manure into bedding, and upon manure decomposition, may release nitrous oxide (N2O), CH4, and ammonia (NH3) into the atmosphere. Manure from grazing livestock is left on fields or paddocks, and the manure may be collected to be treated and stored. Manure that has been collected and stored can be applied to croplands.

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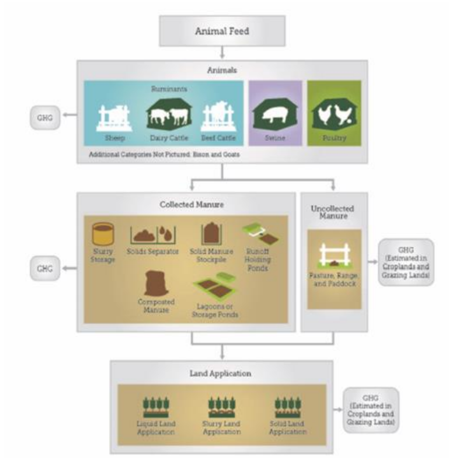

Figure 3: Connections between feed, animals, manure, and GHG for animal agriculture
Source: Powers *et al.*, 2014.

On-farm production of biogas

Biogas is a flammable gas that accrues from the fermentation of biomass in biogas plants. Biogas is produced by anaerobic digestion or fermentation of biodegradable materials such as biomass, manure, sewage, municipal waste, green waste, plant material, and energy crops (Saulter, 2013). This type of biogas comprises primarily methane and carbon dioxide. Together with the reduction of greenhouse gas (GHG) emissions, biogas can enhance energy security, thanks to its high energetic potential (Tricase *et al.*, 2009). Biogas can be used as a low-cost fuel in any country for any heating purpose, such as cooking. It can also be used in modern waste management facilities where it can be used to run any type of heat engine, to generate either mechanical or electrical power. Biogas can be compressed, much like natural gas, and used to power motor vehicles (Kabeyi, & Olanrewaju, 2022). Livestock industries have shown increased interest in biogas (methane) capture-and-use systems, such as covered ponds and the flaring or combustion of the captured biogas to provide heat or power. Biogas generation systems can reduce greenhouse gas emissions and improve farm productivity for intensive livestock farmers mainly pork and dairy farmers (Wang *et al.*, 2021). With a biogas generation system, large volumes of manure are digested under low-oxygen conditions to produce biogas that is subsequently combusted to destroy methane and produce heat or electricity. The waste sludge is normally returned to the land as fertilizer, either as slurry or pellets. Capturing biogas from animal waste also contributes to better air and water quality (Kuo *et al.*, 2017).

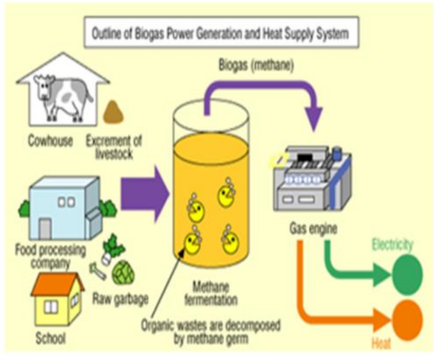

Figure 4: Outline of biogas power generation and heat supply
Source: Saulter, 2013

Enteric mitigation strategies

The enteric CH4 mitigation dataset generated for this document was divided into the following categories: *Feed supplements* (inhibitors, electron receptors, ionophores, plant bioactive compounds, dietary lipids, exogenous enzymes, direct-fed microbials, defaunation, and manipulation of rumen archaea and bacteria) and Feeds and feeding management (effect of feed intake, concentrate inclusion, forage quality and management, feed processing, mixed rations and feeding frequency, precision feeding and feed analyses, and mitigation options for production systems based on low-quality feeds).

Feed supplements

Inhibitors

Research in this area has targeted chemical compounds with a specific inhibitory effect on rumen archaea. Among the most successful compounds tested *in vivo* were bromochloromethane (BCM), 2-bromo-ethane sulfonate (BES), chloroform, and cyclodextrin. These CH4 inhibitors statistically reduced CH4 production by up to 50 percent *in vivo* (in sheep/goat and cattle). Examples are BCM/BES (Mitsumori *et al.*,2011); chloroform (Knight *et al.*, 2011); and cyclodextrin (Lila *et al.*, 2004).

Another more recent study with goats receiving 0.3 g BCM/100 kg BW for 10 weeks (Abecia *et al.*, 2012) reported a 33 percent reduction in CH4 production per unit of dry matter intake (DMI) and increased molar proportion of rumen propionate by close to 40 percent. Knight *et al.* (2011) showed an immediate and dramatic drop in rumen CH4 production in dry cows treated with chloroform.

Feed and feeding management

There is a clear relationship between feed OM digestibility, concentrate feed or starch intake, and the pattern of ruminal fermentation. Thus, it is generally believed that higher inclusion of grain (or feeding forages with higher starch content, such as whole-crop cereal silages) in ruminant diets lowers enteric CH4 production. Beauchemin *et al.* (2011) estimated that implementing extensive forage feeding for growing beef cattle would substantially increase GHG intensity (6.5 percent increase). Similarly, Pelletier *et al.* (2010) reported 30 percent higher total GHG emissions for

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pasture-finished cattle compared with cattle in a grain-based feedlot system.

The effect of dietary supplementation on methane emission was reported by Debruyne et al.

(2018) in kids. The supplementation with coconut oil until 11 weeks of life suppressed the methanogenic activity, inhibiting the colonization of the rumen by *Archea* bacteria, and reducing the *in vitro* emission of methane. Jeong *et al*. (2012) also observed the effect of the inclusion of vegetable oils (coconut, soybean, and palm) on ruminal methane emission, reducing an average of 25% of the emission in relation to animals that did not receive oils. Thus, the use of food alternatives to manipulate the ruminal microbiota to reduce ruminal methane emissions has been widely evaluated and has frequently shown positive results regarding its action. The effect of the inclusion of condensed tannins significantly reduced methane emissions at 12 and 25% of the daily emission rate, due to the inclusion of 2.8 and 5.7 g kg-1 DM from the diet, respectively (Bhatta *et al.* (2013). Condensed tannins inhibit methanogenesis by a direct effect on ruminal methanogens and an indirect effect on hydrogen production due to lower feed degradation (Martin *et al*., 2010).

Concentrate feeding

Concentrate feeds due to higher concentrations of DE than forages usually have a positive effect on the productivity of ruminants. Thus, increasing the proportion of concentrate in the diet should increase animal production and reduce enteric CH4. The effect of concentrate feeds on milk production in dairy cows was demonstrated by Huhtanen and Hetta (2012) and they reported a highly significant and positive relationship between dietary concentrate intake and production of milk, ECM, milk fat, and milk protein. FAO NZAGGRC et al. (2017a, b) estimated that supplementing feed with urea-molasses blocks could reduce emissions intensities by 6 to 12% in dairy systems in Kenya, and between 20 and 27% in Ethiopia. Most intensive dairy producers interviewed report that they use some type of concentrate supplementation, especially during the dry season though few follow recommended feeding regimes, largely due to the high costs involved and low returns from increasing production.

Maize silage

In Kenya, maize silage is gaining popularity as an effective dietary supplement in the context of intensive dairy farming because it reduces enteric emissions of methane (Hristov *et al.,* 2013). These strategies for enteric methane mitigation emphasize increasing feed digestibility, improving rumen fermentation, and using dietary supplements that reduce methane production (Beauchemin *et al.,* 2008). The rising energy content and greater digestibility of maize silage, increase the overall feeding efficiency of livestock and reduce methane fermentation in livestock, thus achieving climate-smart livestock farming (Singh *et al.,* 2023). However, its increased use comes up against difficulties, especially the competition with maize as a human staple food in Kenya. Maize silage is a viable option in regions with erratic rainfall where maize crops frequently fail, especially when supplementary forage sources like sweet potato vines and Napier Grass are included (Kabato *et al., 2*025). Despite these advantages, many farmers do not possess the appropriate skills for producing silage, resulting in inconsistent quality and nutritional deterioration.

To retain feed quality through ensiling, harvesting at the right maturity, chopping, compaction, and airtight storage are some essential techniques that Njogu, 2019, notes. Moreover, the production of maize silage is associated with high input and labor costs, as specialized harvesting, chopping, and storage equipment are not easily accessible for smallholder farmers. The contracting of services for silage production is one emerging solution, providing farmers with professional equipment and expertise at a lower cost (ProDairy E.A. Ltd, 2020). To increase the likelihood of adoption, policymakers and agricultural actors need to implement initiatives aimed at directly training farmers, encouraging the cultivation of alternative forage crops, as well as building the necessary infrastructure to support silage production. Addressing such issues would make maize silage a more sustainable resource and preferred feed for dairy farmers in Kenya, ultimately enhancing livestock productivity while reducing environmental impact.

Conclusions

i. Methane emissions generated by livestock, especially by small ruminants in tropical African production systems, are both an environmental challenge as well as a waste of feed energy. A livestock system's emission intensity is linked to its productivity standards and the digestibility of the feed. There are, however, many mitigation approaches that can both address environmental concerns and enhance animal productivity.
ii. Ideal strategies include altering methane-producing diets through forages, concentrates, oils, and tannins, and improving methane emission ancillary. Microbial alterations like methane inhibitors and compounds that change fermentation patterns in the rumen are very promising technologies. Furthermore, enhanced manure management and biogas production systems can achieve greater emission reductions of GHG while simultaneously generating renewable energy and enriching soil fertility.
iii. Small ruminants in the African tropics may benefit most from strategic supplementation with locally available feeds, improved forage management, and effective simplistically designed manure management systems. Emission reduction associated with sheep and goat production, productivity, and farmer welfare all simultaneously benefit from these tailored mitigation approaches thereby significantly increasing resiliency.
iv. Achieving the balance of reducing emissions of greenhouse gases (GHGs) from livestock while sustaining or improving productivity will be critical for sustainable development of African livestock

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systems, enhancing climate change mitigation efforts as well as food security.

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