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Ruminant contribution to enteric methane emissions and possible mitigation strategies in the Southern Africa Development Community region

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Abstract

The Southern Africa Development Community (SADC) region is not a major emitter of greenhouse gases (GHG). However, Sub-Saharan Africa is considered a potential future hotspot for GHG emissions because of its large livestock population dispersed across large arid lands, coupled with the inherent low digestible feeds in the region and consequently low productivity of livestock. In SADC, climate change is predicted to increase temperatures further reducing agricultural productivity. Therefore, there is incentive to reduce agriculture's contribution to GHG emissions in the SADC region. Ruminant production, a mainstay of rural economy, is predicted to decrease because of diminished grazing due to reduced rainfall and feed quality. However, ruminants' enteric methane (CH_4) production contributes to GHG emissions. This review explores strategies for the SADC region to reduce CH_4 by ruminants. As methanogenesis is an outcome of microbial activity, potential opportunities include selecting animals with inherent low CH_4 production; altering ruminal microbial populations to those that do not yield CH_4; enhancing feed digestibility by feeding additives which improve diet quality and alter the ruminal microbiome and using specific forages such as seaweed or duckweed that contain plant secondary metabolites that may decrease methanogen populations or methanogenesis. These strategies are considered in terms of their potential magnitude of CH_4 mitigation, the practicality for their implementation in the SADC region and their suitability to be included in the grazing-based livestock industries in the SADC region.

Keywords Grazed forage · Greenhouse gas emissions · Methane · Mitigation · Ruminants

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1 Introduction

Livestock production is an important socio-economic activity for most people living in arid environments of the Southern Africa Development Community (SADC). An estimated 75% of livestock are kept under smallholder traditional farming systems (Southern African Development Community 2012). Although ruminant animals (beef cattle, sheep and goats) are the preferred livestock kept in this region, chicken, pigs, horses and donkey are also farmed. Livestock populations in SADC are estimated at 64 million cattle, 39 million sheep, 38 million goats, 7 million pigs, 1 million horses and 380 million poultry (Southern African Development Community 2012). There is a relatively large population of ruminant animals in the region mainly because they are fed on forages that are low-cost sources of nutrients, and therefore, ruminants generally do not compete with humans for food. These animals can convert low-quality forages into high-quality products such as milk and meat which are valuable food resources for many people in the region. These ruminant products supply essential nutrients that play a major role in proper physical and cognitive development of infants, children and adolescents (Leroy et al. 2022) and help promote maintenance of physical function with ageing (Leroy et al. 2022). Furthermore, in the SADC region, ruminants such as cattle provide non-monetised contributions (e.g. draught power and manure), reflecting the importance of integrated crop-livestock farming systems in this region (Otte and Chilonda 2002).

Forages contain variable nutrient composition, namely crude protein (CP), water-soluble carbohydrates (WSC), neutral detergent fibre (NDF), acid detergent fibre (ADF), fat and starch (Rugoho et al. 2016), and as they mature, they become lignified (Cherney et al. 1991). Forages also contain anti-nutritional factors such as tannins (Cowan 1999). The ability of ruminant animals to utilise forage is made possible by the ruminal microbes that are responsible for fermentation processes (Castillo-González et al. 2014). Ruminal microbes that carry out fermentation processes include bacteria, archaea, fungi and protozoa, and they break down feed anaerobically to produce fermentation products namely microbial protein, volatile fatty acid (VFA), methane (CH_4) and carbon dioxide (CO_2) (McDonald et al. 2011). The nutrients produced are also beneficial to both the microbes, and to the host animal, and thus the rumen microbes are in a symbiotic relationship with the host animal. However, the importance of animals as an efficient and economic means of food production has been challenged due to their environmental impacts and the fact that they may compete with humans for food, labour and alternative land uses for arable farming (Mlambo and Mnisi 2019). The shortage of forage is worsened by the increasing human and animal populations. As human and animal populations gradually increase, the demand for food and feed also increases. For instance, the estimated population of the SADC region increased from 327.5 million in 2016 to 337.1 million in 2017 representing a 2.9% annual population growth rate (Food and Agriculture Organisation 2021). As the human population increases, land formerly used for grazing is required for crop production and developments (housing and infrastructure). Therefore, there is a need to optimise livestock feed efficiency through growing and harvesting more forage and increasing its utilization, thereby increasing animal productivity.

Besides increasing animal performance, the need to improve metabolism of ruminants is driven by the fact that ruminants contribute to emissions of greenhouse gases (GHG) into the atmosphere especially CO_2 and CH_4. These gases are produced during fermentation of feed in the rumen. Of the two gases, CH_4 is the most potent GHG as it has a global warming potential 25 times that of CO_2 (Benchaar and Greathead 2011). However, CH_4

is short-lived as its atmospheric life-time is only 12 years compared to 100 to 200 years for CO_2 (Lynch et al. 2020; Allen et al. 2018; Balcombe et al. 2018). From the perspective of national GHG emission targets, agriculture and livestock are an attractive target for CH_4 reduction campaigns as small changes in agricultural emissions could result in large changes in total national GHG emissions (du Toit et al. 2013a). To the best of our knowledge at a national level, South Africa is the only country in the SADC region with data available and livestock contributed 27% to the national emissions (du Toit et al. (2013a), in which beef and dairy cattle accounted for 73%, with beef in extensive system being the highest emitter (83%) compared to dairy (14%) and feedlot (3.2%) in 2010. On the other hand, small ruminants in South Africa contributed 16% of total national livestock enteric CH_4 emissions in 2010, with commercial sheep industry contributing an estimated 91% of sheep emissions, whereas 56% of goat CH_4 emissions originated from the emerging/communal sector (du Toit et al. (2013b). It is possible that these figures are representative of the region since production systems are nearly similar. Therefore, the call for targeted interventions cannot be ignored by SADC countries because in addition to the above ruminant CH_4 contributions, it is predicted that the region will experience drier and hotter conditions as global temperatures increase (Maúre et al. 2018). Some of the worst impacts on sustainable development are expected to be felt amongst agricultural and coastal sectors. For example, it is predicted that global warming of 1.5 °C would lead to an average temperature rise above the pre-industrial baseline in Botswana of 2.2 °C and of 2.0 °C in Namibia (Maúre et al. 2018). These increases in temperatures are predicted to reduce forage yield and quality and may correspondingly increase CH_4 production by 0.9% with each 1 °C temperature rise (Lee 2017). Therefore, there is a need to reduce the environmental footprint of ruminant farming in the SADC region. In addition to its detrimental effects on global warming, enteric CH_4 emissions constitute 2 to 12% of gross energy intake (Mitsumori and Sun 2008), and hence there is a need to reduce CH_4 emissions to improve production efficiency. Notwithstanding the Livestock's Long Shadow (Steinfeld et al. 2006) narrative in which ruminants are purported to produce 18% of global GHG, a re-calculation of GHG emissions by Scholtz et al. (2012) showed that their actual contribution is 4%. The overestimated contribution of ruminants to environment pollution makes them a scapegoat for GHG emissions, whilst their strategic value in the supply of human nutrition and contribution to biodiversity has often been ignored (Scholtz et al. 2020, 2012). In general, the contribution of developing countries to GHG emissions is deemed high due to the legacy of past emissions of long-lived CO_2 and N_2O which strengthens developing countries' contribution to global warming (Ward and Mahowald 2014). However, such CO_2 and N_2O emissions cannot be used to represent the magnitude of ruminal CH_4 production. According to Ward and Mahowald (2014), CH_4 plays a greater role for non-Annex 1 countries, but as has been pointed out by a number of researchers because of the short atmospheric lifetime of CH_4 relative to CO_2, it is erroneous to weight distant past emissions equally with current emissions by the CO_2-eq metric (e.g. Blignaut et al. 2022; Leroy et al. 2022; Scholtz et al. 2020; Lynch et al. 2020). Indeed, it has been suggested that the current emissions weighting scheme leads to unfair punitive polices on ruminant production systems, especially in the SADC region that relies on agriculture and in particular animal agriculture for their rural communities' sustenance (USAID 2015). Agriculture has an important role to play in an effort to reduce GHG emissions and for the maximisation of carbon sequestration (Blignaut et al. 2022). This is despite that SADC's emissions are below the world average per capita emissions, with the exception of Botswana, Angola, Namibia, Zambia, South Africa and the Seychelles who all have world average per capita emissions (USAID 2015). This paper recognised the different pathways that ruminant production contributes to GHG as outlined by Steinfeld et al. (2006) and Blignaut et al. (2022) but would only focus on enteric CH_4 emissions to avoid an expansive scope. Therefore, the objective of this review is to assess to what extent ruminant (cattle, sheep and goats) enteric CH_4 production contributes to global emissions of CH_4 and its effects on the SADC region and possible mitigation strategies.

2 Methodology

Journal articles were identified by using the following search engines; Scopus (https://www.scopus.com/search/), ResearchGate (https://www.researchgate.net/), Google Scholar (https://scholar.google.com/) and Academia (https://www.academia.edu/) specifying the following keywords; agriculture, methane emissions, ruminants, rumen fermentation, rangelands, tannins, phytochemicals, greenhouse gases emissions, Southern Africa Development Community and their various combinations. Gray literature, dissertation or theses were searched from Botswana University of Agriculture and Natural Resources library and included, as well as reports from authors' personal collections. Search was not restricted to year of publication. Old, but classical references (e.g. Hegarty and Gerdes 1999) that lay fundamental concepts to the review were included. However, for most references, where newer articles with similar information or data was identified, the latter were selected.

3 The rumen

To better understand how ruminants contribute to global warming and are able to discuss possible mitigation strategies, an understanding of rumen physiology and microbiology is necessary. It is well documented that the rumen is a rich microbial ecosystem that is colonized by billions of microbes including bacteria, archaea (methanogens), fungi, protozoa, mycoplasma and bacteriophages. There are 10^{10} to 10^{11} bacteria, 10^8 to 10^9 archaea, approximately 10^6 ciliated protozoa and approximately 10^6 fungi/mL of rumen fluid (Cieslak et al. 2013; Kumar et al. 2009). These microbes degrade cellulose, lipids and protein to yield VFA, microbial cells and gases (Morgavi et al. 2010) as illustrated by Fig. 1 from the study by Buddle et al. (2011).

The most important products of ruminal fermentation are VFA and microbial cells. Volatile fatty acids are the primary source of metabolizable energy (ME); for instance, propionate absorbed into the animal is used as the main precursor for glucose synthesis through gluconeogenesis (Rugoho et al. 2019), and microbial cells which are digested further along the digestive tract are the primary source of metabolizable amino acids for maintenance, growth and milk synthesis (Fellner 2009). The VFAs are absorbed across the rumen wall and act as a major source of carbon and energy for the ruminant animal. H_2 is used by methanogens to generate CH_4 which is eructated by the animal and released into the atmosphere (Buddle et al. 2011). Methane is the most potent GHG, and it has a heat of combustion of 55.7 MJ/kg DM (McDonald et al. 2011), and its release to the environment robs the ruminant animal of potential energy. A recent study by Blignaut et al. (2022) estimated CH_4 production as 6.3% of GEI, resulting in a mean relationship of ME equal to 0.9 digestible energy (DE).

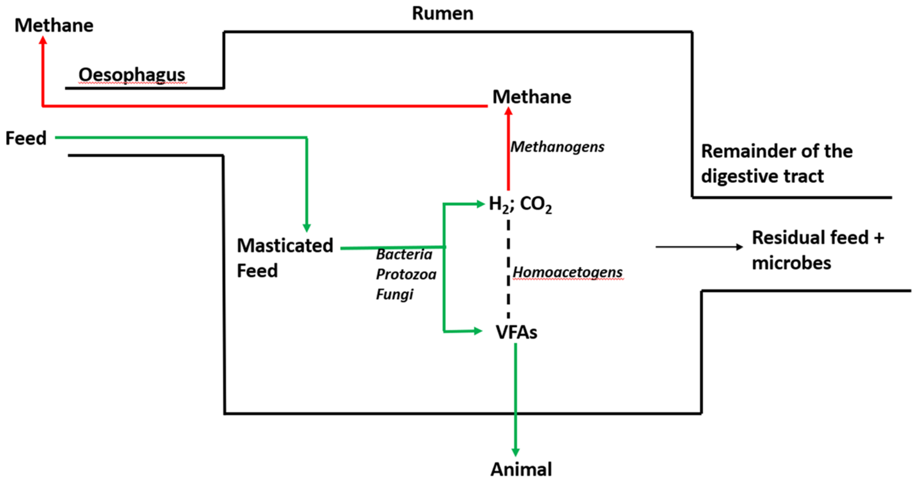

Fig. 1 Diagrammatic representation of some rumen processes, highlighting the microbial fermentation (thick arrows) of the ingested feed to volatile fatty acids (VFAs; mainly acetic, propionic and butyric acids) and to hydrogen and carbon dioxide (H_2 and CO_2). Source: Buddle et al. (2011)

3.1 Methane production in the rumen and its importance

Some of the dominant methanogenes in the rumen include *Methanobrevibacter ruminantium*, *Methanosarcina barkiri*, *Methanobrevibacter formicium* and *Methanomicrobium mobile* (Kumar et al. 2009). Methane is produced as a result of fermentation of hydrolysed dietary carbohydrates such as cellulose, hemi-cellulose, pectin and starch (Beauchemin et al. 2020; Bhatta and Enishi 2007). Other gases produced inside the rumen are H_2 (during the conversion of hexose to acetate or butyrate) and carbon dioxide (Bhatta and Enishi 2007). Ninety-five percent of these gases are released through eructation during rumination (Lee et al. 2017). Methane synthesis is a necessary step for removing H_2, thus propelling the reduction of protons to H_2. Conforming to historical paradigms (Hegarty and Gerdes 1999), a study by Greening et al. (2019) found that hydrogenotrophic methanogenesis appears to be the largest sink of H_2. However, some H_2 sinks are not net H_2 sinks in the sense that their production involves greater H_2 production than incorporation (Ungerfeld 2020). For instance, recent studies (e.g. Roque et al. 2021) have shown elevation of H_2 from inclusion of anti-methanogenic feed additives such as red seaweed (*Asparagopsis taxiformis*) in total mixed ration (TMR) diets, which resulted in decrease in CH_4, and feed intake but improved carcass quality. This work by Roque et al. (2021) is consistent with a metatranscriptomic study by Greening et al. (2019) which reported that whereas methanogenesis-related transcripts predominated in sheep with high CH_4 yield, alternative uptake pathways were significantly upregulated in low CH_4 yield sheep. *Methanosarcina mazei* synthesises CH_4 from acetate, methanol and methylamines, whilst *M. barkeri* utilises H_2/CO_2, acetate, methanol and methylamines for CH_4 synthesis (Jarvis et al. 2000). Thus, in order to reduce the availability of H_2 for use in the synthesis of CH_4, H_2 should be converted into propionate via lactate or fumarate (Asanuma et al. 1999) as shown in Fig. 2 (Morgavi et al. 2010). The recent work by Roque et al. (2021) thus proposes an alternative theory in dealing with high H_2 concentration when anti-methanogenic feed additives such as seaweeds are added; the redirection of H_2 molecules that would otherwise be utilized to

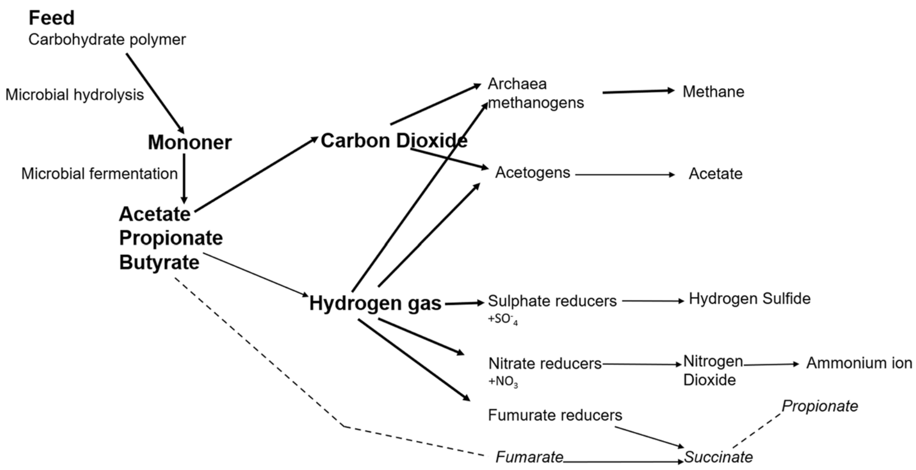

Fig. 2 Schematic microbial fermentation of feed polysaccharides and H_2 reduction pathways in the rumen. Source: Morgavi et al. (2010)

form CH_4 and into different pathways that could be beneficial to the animal. This theory is supported by Greening et al. (2019) to the effect that whereas the enzymes mediating fermentative H_2 production are expressed at similar levels, those supporting H_2 uptake through acetogenesis, fumarate reduction and nitrate ammonification pathways are highly upregulated in sheep with low CH_4 yield. Wang et al. (2018) also noted that when compared with control (TMR with high forage NDF), a non-forage fibre diet increased the production of H_2 by 8.5%, but the production of CH_4 decreased by 14%. This was attributed to shifting of H_2 flow toward propionate, and part of it to H_2 (Wang et al. 2018).

Thus, practical methods that reduce CH_4 emissions should come from multiple pathways. Some of these strategies include feeding legumes, incorporating forages with secondary compounds, providing supplements which improve animal nutritional status and efficiency of feed energy and improved genomic selection (Blignaut et al. 2022). These and other strategies will be discussed later. Formate is also used to produce CH_4, and it accounts for approximately 15–20% of the total CH_4 production in the rumen (Asanuma et al. 1999). Studies by Bhatta and Enishi (2007) and Kumar et al. (2009) have shown that *M. ruminantium*, *M. formicicum* and *M. mobile* utilise H_2, CO_2 and formate to produce CH_4. These methanogenic archaea are attached to the outer surface of ciliate protozoa (Vogels et al. 1980), and thus the removal of protozoa has been reported to decrease CH_4 production (Ushida et al. 1997).

Carbon dioxide is more concentrated than CH_4 in the atmosphere; however, CH_4 is more harmful to the environment than CO_2, because CH_4 is a more potent GHG than carbon dioxide and constitute energy loss for ruminants (Eckard et al 2010). Despite this, the reduction of CH_4 emissions in order to decrease global warming appears to be the most effective in the short term than CO_2 because CH_4 has been estimated to have a chemical lifespan of 12 years unlike CO_2 that has a lifespan of 50–200 years (Moss et al. 2000). Trends in CH_4 emissions and its oxidation can produce long-term trends in stratospheric water vapour. The required temperature for halogen activation allowing heterogeneous ozone-depleting reactions on polar stratospheric cloud (PSC) particles is a function of water vapour concentration (Rosenlof 2018) that facilitate CH_4 emissions. This allows more heat to reach the earth resulting in increased global temperature. The rise in temperatures alters precipitation patterns, causing extreme weather conditions such as floods and high temperatures (Moss et al. 2000) with severe impact on agricultural land, which ultimately affects food security (Masipa 2017). The SADC region is already experiencing fluctuating weather patterns, with delayed rainfall but heavy floods when it rains. In addition to its contribution to greenhouse gasses, enteric CH_4 emissions from ruminants constitute a loss of 2–15% of ingested energy (Eckard et al. 2010; Johnson and Johnson 1995; Moss et al. 2000). This reduces feed efficiency and utilization by the animal. Thus, there is a need to find ways in which CH_4 production can be reduced. Several studies (e.g. Eckard et al. 2010 and Moate et al. 2018) have indicated that feed type influences CH_4 production. Therefore, a feed conceptual framework has been proposed (see Fig. 3) based on several studies reviewed. The agents, when introduced, result in the blockage or minimisation of the red pathways (symbolised by X) but promote the green pathways (Fig. 3), thus reducing CH_4 emissions and increased ruminant productivity respectively.

4 Strategies to reduce methane emissions in the SADC region

Within SADC, countries with the highest agriculture emissions are Angola, South Africa, Madagascar, Zambia, Mozambique, Botswana and Zimbabwe and their agriculture emissions account for 90% of the region's GHGs from agriculture (USAID 2015). This has led Sub-Saharan African (SSA) governments to commit through the Gaborone Declaration for Sustainability in Africa to uphold the United Nations' Sustainable Development Goals and the Paris Accord (Gaborone Declaration 2017). Of the seven SADC countries with highest

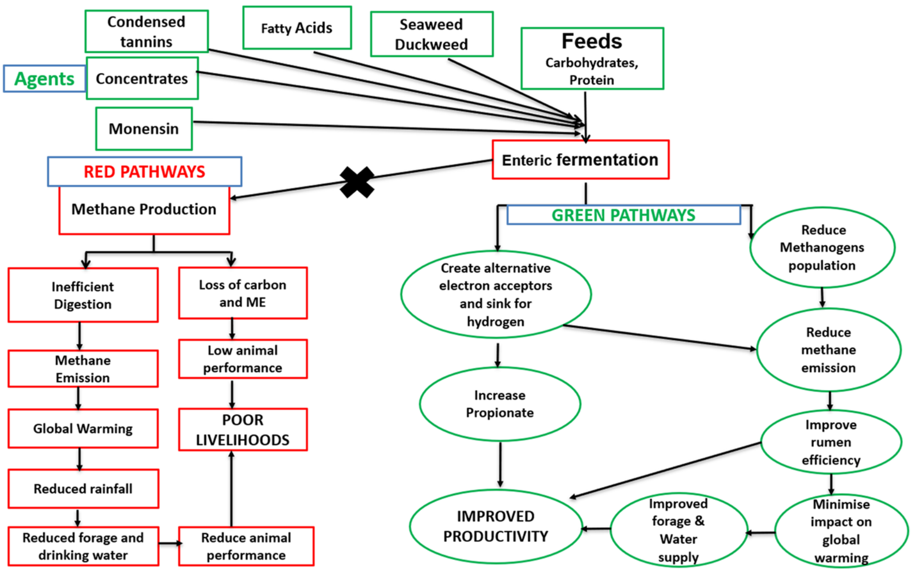

Fig. 3 Conceptual framework on feed manipulation to reduce methane yield in the rumen and improve animal productivity. Green pathway minimises methane production and promotes animal productivity whilst the red pathway yield methane and needs to be blocked

agriculture emissions, enteric fermentation is amongst the top three emitting agriculture subsectors; hence, a range of needs has been identified, including improved livestock, promoting feedlots and using improved feed; promoting livestock breeding and fighting pastureland fires; reduction in emissions from livestock and manure management and biogas captures (USAID 2015) as well as pledges to reduce emissions by 19% by 2030. Therefore, this review is restricted to identifying strategies that are consistent with the above policy commitments by improving the efficiency of ruminant production and hence reduce CH_4 emissions and CH_4 intensities.

4.1 Feeding management and methane production

Feed type, quality and DM intake have been found to affect CH_4 production, e.g. high concentrate diets, leguminous forages, diets containing tannin and diets with high lipid concentration have been found to decrease CH_4 production (Clark et al. 2010). Feeding ruminants more concentrates, e.g. grains, will result in more production of propionate and reduced rumen pH which inhibits the growth of protozoa and methanogens in the rumen resulting in reduced CH_4 production. Grain type is also associated with reduction in CH_4 production as demonstrated by a recent study by Moate et al. (2018) who noted that lactating dairy cows fed wheat (*Triticum*) produced substantially lower CH_4 yield and intensity than when fed rolled corn (*Zea mays*) grain.

However, for the SADC region, feeding ruminants with grains is not a suitable or a sustainable strategy. When reared as nature intended, ruminants should offer very little competition to humans for food because they prefer to consume grass and other fibre-rich forages (Mlambo and Mnisi 2019). Ruminants in developing countries are predominantly maintained on a high-roughage diet with little or no concentrate resulting in increased ruminal methanogenesis (Goel and Makkar 2012) and reduced productivity. Therefore, a challenge for SADC countries will be to make forage more efficient in three ways: (1) increasing fibre digestibility and (2) reducing detrimental effects of tannins on digestibility and (3) taking advantage of tannins to reduce CH_4 production in the rumen. On the other hand, more concentrate, i.e. low fibre intake or excessive intake of rapidly fermentable carbohydrates, causes sub-acute rumen acidosis (Chiba 2009; Rugoho et al. 2019) and should be avoided. Consequently, concentrates should form less than 60% of the animal diet and/or should be even less in the SADC countries where grain for ruminant reaches a prohibitive price. We propose that when grains are weather damaged, or of such poor quality that they are unsuitable for milling and therefore unsuitable for human consumption, then under these circumstances limited amounts of grains may be included in the diets of ruminants in the SADC region. Earlier research (Lichtenwalner et al. 1979) documented higher ash and in situ digestibility of weathered sorghum (*Sorghum bicolor*) grain than nonweathered grains; however, intake was depressed. PennState Extension (2016) cautioned about presence of aflatoxins and mycotoxin in wet grains and provided classification of risks at various mould spore counts in which grains with 3 to 5 million spore count per gram could still be used provided they are diluted with other feeds. An increase in sorghum grain production by farmers, which is agronomically suitable for the SADC region, would fulfil this purpose (Madibela and Lekgari 2005), and inclusion of second grade sorghum grains in ruminant diets would supply tannins that could reduce CH_4 yield. This was demonstrated by Mavasa et al. (2022) who observed reduction in CH_4 yield without reduction in performance of Pedi goats in South Africa when sorghum was used to partially replace maize grain. A study by Beechem (2010) found that the protozoal populations fell by 83% and 76% in cattle fed high and low concentrate diets respectively when treated with ionophores. This indicates that a small amount of concentrate may still be effective, especially to make the rumen more efficient. Hence, a combination of concentrates and ionophores can be used as a strategy to reduce CH_4 production. However, the use of ionophores and other growth hormones is prohibited in some SADC countries. For example, Botswana (Van Engelen et al. 2013) and Namibia were the first African nations to ban the routine use of antibiotics in the beef industry 26 years ago (World Health Organisation 2017). There is a global concern regarding food safety and environmental burden due to use of chemicals (Kobayashi 2010). Therefore, phytochemicals as alternatives to antibiotics to promote growth (Lillehoj et al. 2018) and novel carbohydrate sources to substitute grains should be explored.

Forage quantity, quality and intake are associated with CH_4 production, i.e. the more fibre the forage contains, the more CH_4 is produced in the rumen (Drehmel 2017). Therefore, CH_4 production can be reduced by decreasing fibre content of forages. Alternatively non-forage fibre sources (wheat bran and soyabean (*Glycine max*) hulls) could be used to reduce forage's contribution of NDF (Wang et al. 2018) which was found to reduced CH_4 yield in vitro. Non-forage fibre sources which are derived from crop processing and hence by-products like cereal bran, hulls and husks from post harvesting at farm levels in the SADC region would fit this concept. Furthermore, steers grazing an early season pasture produced approximately 45% less CH_4 than those fed on mid or late season pasture (Boadi and Wittenberg 2002). Hence, forages should be fed or harvested at an early bloom when they have a low fibre concentration. Therefore, mechanisation in fodder production in SADC is important to cut and conserve forages whilst still in a high-quality condition. Manufacture of suitable machinery for small-scale livestock farmers is imperative as demonstrated by Rural Industry Innovation Centre in the 1980s and 1990s in Botswana (Chanda 2000) who manufactured small-scale forage harvesters. Farmers can use appropriate machinery to top up the grass before it lignifies to keep it in a vegetative state thereby improving quality. The starting point would be to encourage livestock farmers to set land aside for fodder production and the use of organic fertiliser (manure) from livestock. Also, in areas with high volumes of water, irrigation might be used to maintain animal forages in an actively growing vegetative (high-quality) state. However, the scarcity of water for irrigation and aridity of much of the SADC region does not make irrigation a viable option for many smallholder farmers. Alternatively, green pasture belts can be developed along rivers and water bodies in the drier parts of the SADC region.

Methane production was 9% higher in cows fed on pasture than on alfalfa (*Medicago sativa*) due to pasture having more fibre in the study by McCaughey et al. (1999). Furthermore, Kurihara et al. (1999) reported that CH_4 energy loss in cattle fed tropical forage diets was higher than in those fed on temperate forage diets due to higher levels of fibre and lignin in the former than the later. For instance, ruminants fed C4 grass species produced 17% more CH_4 as L/kg OM intake compared to those fed C3 grass species (Archimède et al. 2011). A recent modelling study (Lee et al. 2017) predicted that increasing global temperatures will reduce forage quality and correspondingly increase CH_4 production by 0.9% with each 1 °C temperature rise. Considering the already low digestibility of ruminant feed resources from rangelands in the SADC region, this will constitute a serious challenge. Another modelling study by Herrero et al. (2013) expressed non-CO_2 eq emissions per consumed protein from livestock, and their comparisons found SSA as a hotspot for GHG emissions generally because of low animal productivity due to the use of low-quality feeds and feed scarcity. As a result, there is a need for strategies for modifying fibre in forages to reduce CH_4 production. Strategies include the use of alternative grazing species, e.g. adding the foliage of the browse tree legumes like leucaena (*Leucaena leucocephala*) has been shown to improve the quality of low-quality tropical grasses (Santana et al., 2019) and reduce enteric CH_4 emissions (Davison et al. 2020; Piñeiro-Vázquez et al. 2018; Soltan et al. 2017). For example, the inclusion of 80% of leucaena in the diet of heifers fed low-quality tropical forages reduced enteric CH_4 emission by up to 61.3% without affecting DMI, OMI and ruminal protozoal populations in an in vivo study (Piñeiro-Vázquez et al. 2018). The effects of leucaena on reducing enteric CH_4 emission in vitro studies are shown in Table 1.

Other strategies, like reducing the fibre content by adding fibre degrading enzymes during silage production (Khota et al. 2018; Nkosi et al. 2011), would be worth exploring. Under smallholder farming conditions, enzymes may not be accessible, and hence locally available feed additives such as malt may be appropriate (Matshaba 2014). Malted sorghum, for instance, used in small quantities, can be used as an inoculant in silage making. The malting process is incorporated in indigenous knowledge of making traditional beer in the SADC region. Other options entail the use of white rot fungi (*Pleurotus* spp) to disrupt and solubilise lignin of lignocellulosic biomass (Akinfemi et al. 2009; Ntokome et al. 2018) and hence improve digestibility and metabolic efficiency in the rumen. Including millet (*Pennisetum glaucum*), sorghum and maize (*Zea mays*) stover treated with white rot fungi increased CP, in vitro organic matter digestibility (OMD), soluble fraction (a) and effective degradability but reduced ADF and ADL (Ntokome et al. 2018). Type of forage fed to ruminants could play a major role in reducing CH_4 yield with feed management in SADC. For example, legumes from warm climates produce less CH_4 than legumes from cold climates, and that legumes produce less CH_4 than grasses (Archimède et al. 2011). Therefore, tropical legumes with secondary metabolites would be a suitable option within smallholder farms. In addition, tropical legumes with their high CP content can be used in intercropping systems with grasses to improve the overall sward quality and reduce its CH_4 yield potential. Moses et al. (2018) in Botswana observed that when *Macroptilium atropurpureum* (siratro) was used in a pasture mixture including buffel grass (*Cenchrus ciliaris*), not only was the CP content improved, but the degradation lag time in vitro was shortened, and the effective degradability and in vitro dry matter digestibility (IVDMD) were increased. Further research to quantify CH_4 yields from mixed tropical legumes and C4 grass species is needed. The extension message from the above argument would be to provide nutritional supplements that improve the nutritional status of the animal, and the efficiency of feed energy use in order to reduce CH_4 emissions from grazing cattle (Thompson and Rowntree 2022).

4.2 Use of monensin as a feed additive

In the past, major interest for producers, especially in feedlot systems, was the use of monensin for the re-partitioning energy away from CH_4 production to growth for efficient energy utilization. However, in recent times, interest in ionophores use has focused on its ability to reduce enteric CH_4 production. The addition of monensin to ruminant diets has been associated with a reduction of CH_4 production (McGinn et al. 2004; Tedeschi et al. 2003), albeit to a lesser extent than that which occurs in response to feeding sunflower (*Helianthus*) oil (McGinn et al. 2004). In a study by Odongo et al. (2007), CH_4 production was reduced by 7 to 9% when monensin was added to the diet of lactating dairy cows with no effect on milk quantity. However, the long-term use of monensin might lead to rumen microbes developing resistance to antibiotics (Sahoo et al. 2010). Hook et al. (2009) conducted a study to find out if monensin has a significant effect on diversity of methanogens

Table 1 Effects of tannins: source, type, state and inclusion rate on methane reduction both in vitro and in vivo

Plant	Plant/crude extract/ purified	Measurement system	Feed for animals	Inclusion rate	CH_4 reduction (%)	Reference
[a]Acacia mearnsii	Tannin extract	In vivo in sheep	Eragrostis + Lucerne hay:concentrate (50:50)	40 g/kg feed	30% of CH_4 g/kgDM intake	Adejoro et al. (2019)
Silvafeed bypro	Commercial tannin additive	In vivo in sheep	Eragrostis + Lucerne hay:concentrate (50:50)	10 g/kg feed	12% of CH_4 g/kgDM intake	Adejoro et al. (2019)
[b]Acacia nilotica	Plant leaves	In vitro gas production	Natural pasture based on Dichanthium spp	25,50, 75,100% (400 mg feed sample)	+8.2, 14.8, 31.4, 64%	Rira et al. (2019)
[c]Acacia nilotica	Plant pods	In vitro gas production	Natural pasture based on Dichanthium spp	25, 50, 75, 100% (400 mg feed sample)	+4.1, 27, 37.7, 55.1%	Rira et al. (2019)
[d]Moringa oleifera	Leaf meal	In vitro gas production using goat rumen liquor at 48 h of incubation	Replacing soyabean meal in TMR	10, 20, 30, 40, 50, 60, 70, 80, 90, 100 (g/100 g DM)	(% reduction of mL CH_4/g incubated DM) 31.4, 32.4, 49.7, 19.7, 16.9, 19.0, 21.3, 19.7, 16.9, 15.9%	Elghandour et al. (2017)
[d]Moringa oleifera	Leaf meal	In vitro gas production using steer rumen liquor at 48 h of incubation	Replacing soyabean meal in TMR in Steer	10, 20, 30, 40, 50, 60, 70, 80, 90, 100 (g/100 g DM)	(% reduction of mL CH_4/g incubated DM) 20.0, 21.5, 21.5, 17.4, 24.0, 20.0, 10.7, 9.6, 16.0, 11.0%	Elghandour et al. (2017)
[e]Leucaena leucocephala	Leaf meal	In vitro gas production using rumen liquor from Santa Ines sheep	Incubating Leucaena (1000 mg) with low mimosine (2.3 mg/kg DM) after addition of PEG (MW6000)		30.7% of mL/g DM	Soltan et al. (Soltan et al. 2017)

Table 1 (continued)

Plant	Plant/crude extract/ purified	Measurement system	Feed for animals	Inclusion rate	CH_4 reduction (%)	Reference
[e]Leucaena leucocephala	Leaf meal	In vitro gas production using rumen liquor from Santa Ines sheep	Incubating Leucaena (1000 mg) with low mimosine (11.1 mg/kg DM) after addition of PEG (MW6000)		19.4% of mL/g DM	Soltan et al. (2017)
[e]Biophytum petersianum [f]Acacia mangium	Leaf meal	In vitro gas production using rumen fluid from Ongole crossbred cattle	Basal grass of *Pennisetum purpurem* (80%) supplemented with *B. petersianum* or *A mangium*	20% 20%	25% 29%	Hariadi and Santoso (2010)

[a]Acacia mearnsii contained 0.651 g/g DM total phenol, 0.58 g/g DM total tannin (as tannic acid equivalent) and 0.35 g/g DM of CT (as leucocynidin equivalent)

[b]Acacia nilotica leaves contained 80 g/kg DM CT, 31 g/kg DM gallotannins and 147 g/kg DM ellagitannins

[c]Acacia nilotica pods contained 157 g/kg DM CT, 84 g/kg DM gallotannins and 266 g/kg DM ellagitannins

[d]Cannulated Creole Goats and Holstein steers were fed ad lib with a diet consisting of oat hay and concentrate at 60:40 ratio

[e]Cannulated Santa Ines sheep ($n=6$) grazed *Brachiaria decumbens*, *Pennisetum purpureum* and *Leucaena leucocephala* and supplemented with graze maize and soyabean (0.7 kg/100 g LW) and free access to mineral premix

and found that it does not have a direct effect on the methanogen population. It has been reported that ruminal ciliate protozoa are reduced by initial ionophore exposure, but that long-term exposure to monensin led to recovery of the ruminal population (Guan et al. 2006). This is also an issue for microbes developing resistance to antibiotics. Moreover, a study by Rogers et al. (1997) showed that the extent of reductions in total ruminal protozoa numbers as a result of monensin supplementation decreased with time. Many methanogens are found in association with ciliate protozoa, and there is evidence they live on the outer surface of the protozoa (Krumholz et al. 1983; Newbold et al. 2015).

Although monensin is effective in reducing CH_4 production, it is believed that the continuous use of antibiotics will end up with their residues reaching the human food chain (Odongo et al. 2007). This should be avoided because antibiotic residues may induce pathogenic microbes that inhabit the human gastrointestinal tract to develop resistance to antibiotics. In countries such as Botswana and Namibia, the ban on chemicals like monensin (Van Engelen et al. 2013; World Health Organisation 2017) means that other alternatives should be explored (Lillehoj et al. 2018). For example, a possible alternative is tannins as they have been shown to reduce enteric CH_4 production (Greathead 2003; Rira et al. 2015, 2019). Feeding forages containing plant secondary metabolites (i.e. saponins, tannins and essential oils) to ruminant animals could be used as a strategy to reduce CH_4 production by ruminant animals. In addition, in contrast to ruminant agriculture in developed western countries where cattle are often fed TMR, ruminant production in the SADC region is based on grazed pasture where monensin has been found to be ineffective at reducing methanogenesis. Therefore, besides the ban on production enhancing chemical, the use of monensin in ruminants grazing natural pasture would be irrelevant in the SADC region due to very little or no effect on CH_4 emissions (Grainger et al. 2010).

4.3 Use of tannins as feed additives

Tannins are plant secondary compounds that are not involved in the primary biochemical process of plants, but act as plant protection mechanisms (Silanikove et al. 2001). They have antimicrobial activity (Cowan 1999), they protect plants against insect attack (Ørskov 1998), and as tannins are astringent and unpalatable, they dissuade animals from grazing tanniniferous plants (Barbehenn and Constabel 2011). Tannins are divided into two groups, namely condensed tannins (CT) and hydrolysable tannins (HT) (Lee 2017). Condensed tannins are found in gymnosperms and angiosperms whilst HT are found only in dicotyledons (Silanikove et al. 2001). Local forages and fodder trees in the SADC region are endowed with polyphenolic compounds including both condensed and hydrolysable tannins (Madibela et al. 2018; Phale and Madibela 2006). However, there is limited evidence (Theart et al. 2015) on the use of African forages containing secondary metabolites to reduce CH_4 yield apart from few studies done outside the SADC region (see Table 1). The effects of African forages containing secondary metabolites on CH_4 yield need more study in the SADC region.

Nevertheless, based on an extensive findings in the scientific literature, tanniniferous plants should be incorporated in ruminant diets in the SADC region as they are well adapted to the semi-arid conditions and tend to produce nutritious browse products well into the dry season (Mlambo and Mapiye 2015). However, diets with high CT concentrations (> 55 g CT/kg DM) generally reduce voluntary feed intake and digestibility and are associated with low rates of body and wool growth in grazing ruminants (Min et al. 2003). On the other hand, Tiemann et al. (2008) reported that CT reduces CH_4 production by reducing fibre digestibility, perhaps because CH_4 production is associated with highly fibrous feed material. However, the study by Carulla et al. (2005) found that black wattle (*Acacia mearnsii*) containing 0.6% CT reduced CH_4 production without decreasing fibre digestibility. The challenge, therefore, is to identify cost-effective components (of plants and their type) (Bodas et al. 2012) that favourably modify ruminal fermentation to reduce CH_4 production without reducing production by decreasing digestibility. For instance, in an in vitro study conducted with fodder material from the Thorny Kalahari Dune Bush veld of South Africa, Theart et al. (2015) found that samples of kalahari-sand acacia *(Acacia luederitzii*) and blue bush (*Monechma incanum*) with total tannin content of 299 and 283 g/kg, respectively, substantially reduced CH_4 yield without adversely affecting organic matter digestibility (OMD). The effects of tannins in reducing CH_4 production depend on its concentration in plants, composition of the diet, animal physiological state and animal species (Makkar 2003) and whether it occurs as HT or CT (Aboagye and Beauchemin 2019; Rira et al. 2019). Condensed tannins have other benefits to animals such as promoting increased liveweight gain and decreased severity of infestations by gastrointestinal parasites (nematodes) (Mata-Padrino et al. 2019; Min et al. 2003). Because of this inverse relationship between CT concentrations, type and structure with voluntary feed intake and fibre digestibility in ruminants, forages that contain high levels of tannins need to be mixed with those that do not contain any tannins or contain less CT to reduce their adverse effect on feed intake and digestibility. For example, farmers in the SADC region have adopted feeding tanniniferous plants as part of strategy for suppling essential limited nutrients and improving liveweight gains as demonstrated by Brown et al. (2018) in South Africa. This strategy involves harvesting tree foliage and collection of pods to offer as supplementary ration, especially during the dry season (Smith et al. 2005) reducing mortality of twin kids and improving goat performance in Zimbabwe. Other than tannins, fatty acids (FA) are also believed to reduce CH_4 production when incorporated in animal diets (Beauchemin et al. 2008, 2009; Soltan et al. 2018).

4.4 Use of fatty acids as feed additive

Polyunsaturated FA (PUFA), e.g. linoleic and linolenic acids, and medium chain FA (MCFAs), e.g. lauric and myristic acids, have been reported to reduce CH_4 production when included in animal diets (Eugène et al. 2008). This is mainly due to their toxic effect on bacteria, protozoa and methanogens (McAllister et al. 1996). Sunflower seed, linseed (*Linum usitatissimum*), coconut (*Cocos nucifera*) and rape (*Brassica napus*) seed are the main source of PUFA and MCFAs (Rasmussen and Harrison 2011). Beauchemin et al. (2009) using lactating dairy cows noted a 10% decrease in CH_4 production in cows fed on diets containing 3.3% DM of sunflower seed. In the study by (Beauchemin et al. 2009), the addition of sunflower seeds to the diet of dairy cows resulted in reduced CH_4 production with no change in rumen pH and milk production. Just like sunflower oil, linseed oil also contains a high concentration of PUFA (18:3) (Rasmussen and Harrison 2011), and addition of linseed oil (3.3% DM) to the diets of dairy cows reduced CH_4 production by 18% with no effect on rumen pH (Beauchemin et al. 2009).

Canola (*Brassica napus*) seeds contain high concentrations of medium unsaturated FA (18:1), and when it was included in the diets of dairy cows (3.3% DM) it reduced CH_4 production by 16% (Beauchemin et al. 2009). The variability in CH_4 production resulting from dietary addition of these oil sources indicates that the types of FA and their concentrations determine the amount of CH_4 reduced. However, fat should not exceed 6% of the diet of ruminants because too much of it will cause digestion disorders (Machmüller et al. 2000). The sources of FA outlined above are not produced in large quantities in SADC, except for sunflower. Recently canola has been introduced in South Africa and its adaption and adoption will contribute to a variety of ingredients that can be used in ruminant's diets. This calls for investigations into other sources of lipids and essential oils that are locally available, especially from indigenous plants, as ruminal fermentation modifiers. For instance, Ramathudi (2016) estimated in vitro CH_4 reduction potential of 51.2, 43.4 and 40.8% by coating maize stover with lipids from *Ximenia caffra*, *Racinus communis* and *Citrullus vulgaris* respectively, at 5% inclusion. Studies outside the SADC region have also reported that dietary inclusion of essential oils reduces CH_4 emissions (see Table 2).

Dietary inclusion of essential oils is believed to reduce CH_4 emissions by shifting the microbial fermentation in the rumen to decrease the acetate to propionate ratio (Castillejos et al. 2007; Ebeid et al. 2020). However, some oils such as Moringa (*Moringa oleifera*) seed oil, in addition to their broad-spectrum antimicrobial activity, are rich in sterols and antioxidants such as polyphenolic compounds, α-tocopherol (134 mg/kg) and vitamin E which can potentially affect microbial diversity and fermentation process in the rumen (Ebeid et al. 2020). Even though positive results on CH_4 reduction by essential oils have been observed in vitro, this was accompanied by negative effects on DMD by some essential oils unless included as a combination of oils to provide a synergistic associative positive effect (Cobellis et al. 2016) (Table 2). Therefore, the challenge remains to identify essential oils that selectively inhibit rumen methanogenesis at practical feeding rates, with lasting effects and without depressing feed digestion and animal productivity (Benchaar and Greathead 2011). One strategy is the use of essential oil or oil from plants from small-scale cottage industries which process seed for oil either for food, biofuel or cosmetics. Essential oil and/or cake from such processing would be made available as feed additives or feed cake to supplement ruminants supplying the needed FA to reduce CH_4 yields. For example, cottage industries in Botswana and Namibia in which morula (*Sclerocarya birrea*) fruits are harvested by women groups and processed for cosmetic oil have resulted in a seed cake used as a source of energy and protein which Baleseng (2022) found to improve growth rates of local sheep. Due to exports sanitary compliance to European Union markets, feeding material considered as natural products such as seaweeds to ruminants will be attractive to SADC farmers. Seaweed (known as marine algae) has a tradition of being part of the animal feed in the coastal areas, from ancient times (Morais et al. 2020). Feeding livestock seaweed has been shown to reduce CH_4 production (Vijn et al. 2020) and will be suitable for circumventing effects of feed shortage in the SADC region. Angola, Mozambique, Namibia and South Africa have access to a long coast from the Atlantic to India oceans, and hence there exists an opportunity for harvesting and/or farming of seaweed.

4.5 Potential use of red seaweed and other aquatic plants in reducing methane yield

Recent research has shown the potential of seaweed in reducing CH_4 yield in ruminants. Studies by Machado et al. (2014) and Maia et al. (2016) noted high reduction of CH_4 in vitro, with inhibition of more than 90%. In support, feeding studies (Roque et al. 2019, 2021) with dairy cows and beef steers respectively fed TMR-based diets observed CH_4 reduction of 26.4 vs 67.2% and 69 vs 80% and as a result of inclusion of seaweed *(Asparagopsis* spp) at rate of 0.5% vs 1.0% and 0.25 vs 0.5% respectively. Other aquatic plants with feeding possibilities are *Azolla* (i.e. *Azolla filiculoides*), *Salvinia* (i.e. *Salvinia molesta*) and

Table 2 Effects of essential oil and inclusion rate on methane reduction both in vitro and in vivo

Plant	Plant/crude extract/purified	Measurement system	Feed for animals	Inclusion rate	CH_4 reduction (%)	References
[a]Pequi	Essential oil	In vitro gas production with rumen fluid from Holstein crossbred	TMR of corn silage, Tifton 85 concentrate and minerals	5% v/v of inoculation media	86.7% CH_4 (24 h mL/g DM incubated)	Freitas et al. (2018)
[b]Pequi	Essential oil	In vivo in Dorper sheep in respiration chamber	TMR of corn silage, Tifton 85 concentrate and minerals	75 mL oil/animal	17.7% of CH_4 g/kgDM intake	Freitas et al. (2018)
[c]Agolin Ruminant	A blend of essential oils (coriander oil, geranyl acetate and eugenol)	Four multiparous lactating Holstein cows in open circuit chambers	Fed mixture of grass silage, maize silage and soybean meal and supplemented with concentrate	200 mg essential oils/animal	15% (g/d) and 14% (g/kgDMI)	Castro-Montoya et al. (2015)
[d]Agolin Ruminant	A blend of essential oils (coriander oil, geranyl acetate and eugenol)	Four Belgian Blue double muscled beef heifers in open circuit chambers	Fed maize silage ad libitum and supplemented with concentrate	200 mg essential oils/animal	Ranged 13% and 20% (g CH4/kg BW)	Castro-Montoya et al. (2015)
[e]Moringa oleifera	Seed oil	In vitro using rumen fluid from three crossbred (Murrah × Chinese local) water buffaloes. Methane measured using GC system	TMR of Roughage 70:Concentrate 30 was incubated	4% of sample incubated	48.4% of CH_4 L/g DM	Ebeid et al. (2020)
[f]Cinnamon leaves	Essential oil	In vitro using fluid from lactating Jersey cows Methane measured with GC	Alfalfa hay and a concentrate mixture (ground corn, soy hulls, soybean meal and a mineral/vitamin mixture)	1.125 mL/L culture	69.2% of mL CH_4 (24-h incubation)	Cobellis et al. (2016)

Table 2 (continued)

Plant	Plant/crude extract/purified	Measurement system	Feed for animals	Inclusion rate	CH_4 reduction (%)	References
[g]Combination of cinnamon leaves, oregano leaves, rosemary leaves	Essential oils	In vitro for using fluid from lactating Jersey cows Methane measured with GC	Alfalfa hay and a concentrate mixture (ground corn, soy hulls, soybean meal, and a mineral/vitamin mixture)	0.8 mL/L total	78.5% of mL CH4 (48-h incubation)	Cobellis et al. (2016)

[a,b]Pequi contained on g/100 g basis; 0.08 lauric acid, 0.12 myristic acid, 27.1 palmitic acid, 2.57 stearic acid, 44.7 oleic acid, 21.1 linoleic acid, 1.95 linolenic acid and 0.21 arachidic acid. The incubated material was Tifton 85 hay with 3 increasing levels (1, 2 and 5% (v/v)) of oil

[c,d]Each animal received a daily dose of 200 mg essential oils, which was homogenously mixed with part of the concentrate

[e]The study does not indicate what type of material was fed to the cannulated buffaloes

[f]Jersey cows fed on corn silage, mixture of alfalfa hay and grass hay and concentrate mixture

[g]Jersey cows fed on corn silage, mixture of alfalfa hay and grass hay and concentrate mixture

Lemna (i.e. *Lemna minor*). However, limited literature (Chakrabarti et al. 2018; Goopy and Murray 2003; Halmemies-Beauchet-Filleau et al. 2018; Leterme et al. 2009; Sońta et al. 2019; Zakaria and Shammout 2018) report only the production capacity and feeding value indicating endowment with high protein and amino acids concentration, high trace minerals and high DMD. However, experimental studies have mainly focused on poultry and pigs (Leterme et al. 2009; Mwale and Gwaze 2013; Zakaria and Shammout 2018). An early study by Huque et al. (1996) recorded high mean CP (32.7%) of three duckweed (*Lemnoideae*) species with DM and CP digestibility of 57 and 68.2% respectively. To our knowledge, there is no study which has reported their CH_4 reducing potential and hence a worthy research area. The studies mentioned earlier, on seaweed, both in vitro and in vivo, demonstrate that seaweeds could play an important role in reducing CH_4 in ruminant production, an innovation which the SADC region can adopt. For instance, South Africa has a costal length of 2850 km, Namibia has 1500 km, Angola has 1600 km, whilst Mozambique has 2600 km and therefore could be a source of seaweeds and/or foundation for commercial farming of seaweed. Notably, seaweed is currently being used to produce commercial chicken feed products and feed supplements for livestock farms in South Africa (Matshogo et al. 2021). However, it is important to note that innovative strategies which use seaweed to reduce enteric CH_4 have been developed for feeding to ruminants on TMR based diets which might be impossible in grazing-based ruminant systems in the SADC region. However, used as supplements, these can still find a niche in the grazing-based systems where animals are conditioned to return to a watering point every day or alternate day for watering and mineral licks. As a matter of practice, grazing ruminants in the SADC region, especially for 70 to 90% of cattle owners who are small-scale resource limited farmers (Statistics Botswana 2019), are brought to watering points, which consist of pens and handling facilities to be watered or kraaled overnight. With regard to other aquatic plants such as duckweed and Salvinia which customarily invade water bodies and wetlands in SADC like the Kariba Dam in Zimbabwe and Okavango Delta in Botswana, physical harvesting has been found to have limited but effective control (Kurugundla et al. 2016). Therefore, management with utilization for livestock feed can be mounted in locations where livestock are reared proximal to these water bodies. Alternatively, local on-farm production in ponds incorporating nutrient scavenging from field runoff, manure and greywater may offer a viable possibility for ruminant feed production and thus reinforce circular economy practices at farm level and decrease the environmental footprint of ruminant-based food production systems (Halmemies-Beauchet-Filleau et al. 2018). The strategies outlined above would serve as short- and medium-term approaches, and in the long term, selecting animals with inherent ability to produce less CH_4 would be sustainable.

4.6 Genetic selection of ruminants for low methane emissions

Although the magnitude of emissions of CH_4 expected to be reduced by selecting for low CH_4 ruminant animals is small about 7% (Davison et al. 2020), mitigation of enteric CH_4 emission by genetic selection has become an important area of research in many regions of the world, e.g. Richardson et al. (2021) in Australia. One area of research interest is selecting for feed efficiency using residual feed intake (Basarab et al. 2013; De Haas et al. 2011) which was observed to have heritability of about 0.26 to 0.58 (Hendriks et al. 2013). The use of genetic and phenotypic correlations of CH_4 outputs with various production traits could also be of considerable use for identifying more efficient animals (Pinares-Patiño et al. 2013). Application of genomics opens the possibility to efficiently select for hard to measure traits (Oddy et al. 2014). For instance, application of genomics to identify rumen microbiota related to CH_4 and their association with cattle feed efficiency (Hernandez-Sanabria et al. 2012) would not only be fast but an efficient way of formulating feeding manipulation strategies to reduce CH_4 emissions. The development of these proxies with high correlation with CH_4 production would be beneficial for identifying animals with low CH_4 emissions (Negussie et al. 2017). Once these genetic biomarkers for low CH_4 emissions have been identified in Western breeds, the same genetic biomarkers might, in the future, be able to be used to select low CH_4 emitting cattle of African breeds.

5 Conclusion

Based on the present review, use of alternative grazing species, e.g. leucaena, on-farm pasture management, use of seaweed, tannins, FA, concentrates and the use of genomics are possible strategies for reducing rumen CH_4 production in the SADC region. Use of cereal crop residues needs bioprocessing to improve nutritive value and digestibility, hence making rumen metabolism more efficient. These will depend on the region's strategy for SDGs and the Paris Accord as some of the proposed interventions will compete with humans for food such as the use of concentrate and edible oil. However, condensed tannins, lipids and essential oils from indigenous plants (forages, trees and shrubs) including seaweed could play a critical role in manipulating rumen fermentation to mitigate CH_4 production in this region. When implementing these mitigation strategies, the region should not lose sight of global distorted CH_4 accounting that focuses on isolated overemphasised metrics. Such overestimating of emissions and inflated effects of CH_4 from ruminants may result in unnecessary costs further impoverishing resource limited communities in the SADC region.

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Declarations

Competing interests The authors declare no competing interests.

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