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Handbook of Climate Change Mitigation and Adaptation

Third Edition

Springer

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Third Edition

With 1088 Figures and 347 Tables

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To Konrad Steffen (2 January 1952–8 August 2020), a Swiss-American climate scientist who died on a research field trip to Greenland, when he fell into a crevasse. Before deglaciation, such crevasses were not known.

To the 5 million people, whose annual premature deaths are linked to climate change already now.

To those who will take action in the future to combat climate change, for all of us.

Foreword

The first two editions of this *Handbook* have already established it as an essential tool for the increasing number of theoreticians and practitioners working in the overlapping fields of the climate and life sciences, socio-economics, engineering, and even aesthetics and philosophy. The first edition had 2130 pages, 586 figures, and 205 tables; the second one 3331 pages, 1108 figures, and 352 tables.

This third edition is clearly even bigger and better. As we get ready to plunge into it, it is worth stopping for a moment and reflecting on the evolution of what has become an important field of and onto itself, namely, that of *Climate Change Mitigation and Adaptation (CCMA)*. This foreword dwells on three important topics for this field: (i) the communication problems of interdisciplinarity; (ii) the crucial role of the times in which we live for the future of humanity on this planet; and (iii) the impact of stakeholders on the science we conduct.

To start with (i), it is well known that living at or near a border is potentially very interesting but it is often also quite difficult. This statement is especially true in the sciences, where speaking a different language makes mutual understanding harder, as does having grown up with an often very different type of education. Ludwig Wittgenstein already pointed out the difficulties involved in communication among different "language communities," into which he definitely included scientific communities.

It is thus important to keep in mind, as CCMA develops its own language, that this language should be rich and creative in and of itself, but also draw on the neighboring languages of the separate communities that have contributed to its birth and are continuing to nurse it. To put this less philosophically and more concretely, Integrated Assessment Models (IAMs), as an important dialect of the new CCMA language, need to balance the requirements of both climate and economic modeling: the former deeply anchored in a physical language, in which the basic rules are natural conservation laws, the latter in a socioeconomic language, in which the rules are more empirical and consensus-driven but equally important.

There is, however, a truly striking case of a phrase jumping the language barrier; that phrase is "tipping points." Sudden jumps from one steady state of a system to another were originally studied by Leonhard Euler, three centuries ago. Euler formulated and solved a mathematical model for the buckling of a beam, i.e., for its sudden transition from a straight to a curved state, as the axial load on it is increased past a critical value. Such a transition became known as a *bifurcation.* Bifurcations were generalized in the mid-twentieth century from saddle-node bifurcations between two steady states to Poincaré-Andronov-Hopf bifurcations between a steady state and a cyclic behavior and, in the later twentieth century, to various forms of transition between periodic and chaotic types of behavior, dubbed routes to chaos.

Unaware of this rich history – which involved applications of bifurcation theory to a plethora of problems in the physical, biological, and even socio-economic sciences – a journalist, Malcolm Gladwell, had the intuition that such sudden transitions due to "little things," like a small change in a parameter value, could play a big role in sociology. His book, published in 2000, became a bestseller and the phrase took off. Tipping points are now everywhere, and they have even been given a precise mathematical definition as bifurcations in dynamical systems subject to time-dependent forcing. Relevant examples are the bimodalities in sea ice cover of the Arctic and in the vegetation cover of the Amazon basin; in both cases, the time-dependent forcing to be considered is the anthropogenic change in atmospheric composition and, hence, optical properties.

Turning now from mere linguistics issues to Earth- and humanity-shaking ones, the realization that we are at a crossroads is truly sinking in. The 2020s decade that just started has already been called the "Soaring Twenties," a wink to the post-WWI "Roaring Twenties." It is a decade that, by most accounts, will play a key role in the coevolution of humanity and its planet. While there is still no dearth of incredulous or uninformed people – in countries large and small, advanced and developing – the overwhelming consensus of informed opinion is that we have to change our spendthrift collective ways and do something to prevent the young generation and the following ones from suffering greatly.

But what exactly do we have to do about climate change? CCMA, as a field of science and engineering, has a lot to contribute to the multiple answers to this question. These answers need to also take into account that there are many other issues involved in humanity's current and future well-being than climate change: loss of biodiversity is due to human population pressure and not just to climate change; regional and social inequalities affect and are affected by climate change, and so on and so forth. One rapidly emerging fact is an increasing commitment from the giants of private business to chart a course that aligns with the approximately right direction of achieving "net-zero" carbon emissions by mid-century or earlier. Another such fact is the rapid emergence of "green finance" and, more generally, of investment that is driven by, or at least affected by, so-called *environmental, social, and governance (ESG)* criteria.

Up until recently, the efforts of climate and environmental activists and of their large crowds of followers have focused on convincing public decision-makers to deploy the means of states and international institutions in support of the requisite steps for a better future. More recently, the resources of both public and private finance, to the tune of tens of trillions of dollars, are seeking environmentally sound investments to maximize growth and mitigate risk, and the private portion is much larger than the public one. The risks incurred by such investments are transitional – i.

e., those associated with mitigation policies – as well as physical, such as asset losses due to climate change and variability. Still, the increased private-capital interest appears to be going, more and more, beyond "greenwashing" and on to real action.

And here we are getting to the third and last part of this foreword. Most private institutions, including the largest ones, do not have the same experience with fostering science in support of their goals as public ones do. Maximizing an investment bank's growth and mitigating its risks might not always harmonize with the lofty goals of saving the planet and optimizing humanity's life on it. Just to give one small example, private capital is much more in tune with the traditional measure of national and global success, namely, gross domestic product (GDP). But it has become clearer and clearer that GDP is not the unique and not even a good measure of individual or community happiness.

Over the last decade, it has been forcefully argued that the Inclusive Wealth Index (IWI) is much better at measuring welfare and not just production. It is important, therefore, to use IWI and, possibly, other multi-index measures in projecting the state of the world into the future, no matter what certain powerful stakeholders in this future might think.

A final scientific point concerns the uncertainties in such projections. It is these uncertainties that must be taken into account in deciding "what exactly do we have to do?" Beyond the well-known, and multiply attributed, saying about "the known unknowns and the unknown unknowns," there's not much one can do about the latter. But there are many ways to take into account the former. Uncertainty quantification has become a flourishing field in the sciences and engineering. The financial industry has, obviously, its own ways of quantifying uncertainty – ways which are quite sophisticated and well adapted to its purposes but are quite different from those that are used in the climate and ecological sciences. Once more, there's a language problem, and we're back to the first topic on our list.

The topics that were touched upon in this foreword are, naturally, just three out of many. I can only wish this *Handbook's* third edition all the success it deserves and hope that some heed will be paid to these topics in future editions as well.

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Michael Ghil

Preface

The third edition of the Handbook, printed 10 years after publication of the first edition, has arrived. Meanwhile, the Keeling curve has moved from 394 to 419 ppm, and evidences of the devastating climate changes have emerged, such as the complete loss of stability of the natural Atlantic Meridional Overturning Circulation (AMOC) (Boers 2021). We have also learned more about climate change and mitigation, which will be the emphasis of this edition. But what is in knowledge?

"The more I know, the more I realize I know nothing." Socrates

"The more I learn, the more I realize how much I don't know." Albert Einstein

With more knowledge also come uncertainties, and science needs to and does look at them. Climate change has been a political topic ever since. The oil lobby has been accused of denying climate change. A notorious memo from 1998 reads: "Victory will be achieved when average citizens recognize uncertainties in climate science" (https://www.govinfo.gov/content/pkg/CHRG-116hhrg38304/html/CHRG-116hhrg38304.htm, accessed August 8, 2021). It is not that simple, though, to merely demonize one industry. Climate change, this is all of us. And victory can be for no one.

Today, "sustainability" has become somewhat of a hype. Be it circular economy, meat consumption, energy use, resource consumption, carbon emissions – the feeling has emerged that both organizations and private citizens all over the planet have started to recognize that something with the current way of living is wrong. But do we see countermeasures or a changing trend? The COVID 19 pandemic was an unprecedented caesura, yet its effect on our climate is estimated on only 0.01 °C of avoided warming (https://www.bbc.com/future/article/20210312-covid-19-paused-climate-emissions-but-theyre-rising-again, accessed August 8, 2021).

This Handbook makes a contribution by offering an up-to-date, comprehensive collection of knowledge on climate change adaptation and climate change mitigation.

It is up to you, the reader, to take this knowledge and put it into action.

The editors of this Handbook want to thank all authors for sharing their research, and the publishers for enabling this format. The next decade is definitely a decisive one for our climate. Let us all act within our own sphere of influence. Like every molecule of CO_2 counts, it is every step, large or small, in the right direction that is of value, and remember that the first steps are always the most important ones.

April 2022 The editors

References

Boers N (2021) Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. Nat Clim Chang 11:680–688. https://doi.org/10.1038/s41558-021-01097-4. Accessed 8 Aug 2021

Prologue

Climate change is a global issue that will affect all of us. Its negative effects have already begun and are felt on all parts of the planet, from the poles to the equator.

The concept and theory of the greenhouse effect have been described and studied for almost two hundred years, and the question of whether or not our anthropogenic activities affect the climate has been asked and answered for almost as long. Since the second half of the twentieth century, it has become apparent that we humans cause the climate to change due to modern societies' emissions of greenhouse gases, and now the science is clearer than ever. The climate is changing rapidly due to our human activities. If we do not address this issue and immediately act on mitigating it, the consequences will be potentially devastating. We can no longer ignore the facts.

Scientists studying climate change and its effects have called out for change and action for decades. They have warned the public, governments, and companies that we need to act, and that we need to act now.

However, for some reason, these warnings have seemingly passed unheard. Despite scientists urging for climate action, little has happened. Now, in the last few years, climate change has risen substantially on the international agenda. Apart from the few denying climate change, the majority agrees that something needs to be done. Still, large-scale action is yet to be seen. It seems as though society is paralyzed. Action from politicians, financial leaders, and others with the power and mandate to enact action is yet far too slow and far too little compared to what needs to be done.

The current inaction toward climate change could be described as though we are performing a collective global experiment on our earth's climate, with both nature and ourselves as the metaphorical guinea pigs. This being said, all is not yet lost. Science does not only tell us what the issue is and where it stems from, but also provides us with the tools and insights necessary to resolve the problem of anthropogenic climate change. So, to stop this enormous high-stake gamble with our planet, its ecosystems, as well as our own lives and futures, we need to collectively act and demand real, sustainable climate action from those with the economic and political mandate to enable large-scale change. With said change being rooted in science, democracy, and sustainability. It is not an impossible task, but it is a necessary one.

The climate crisis is a global crisis, and it is time to act accordingly. Listen to the science.

Alexander Ahl, Isabelle Axelsson, Alde Fermskog, Ell Jarl, Greta Thunberg
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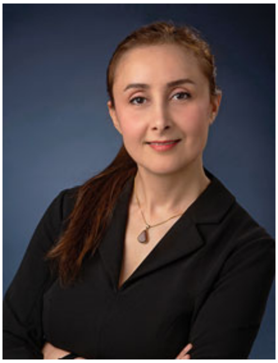
Dr. Maximilian Lackner is study programme director of the Master "Innovation and Technology Management" and "International Business and Engineering" at the University of Applied Sciences FH Technikum Wien, Vienna, Austria. He has obtained his PhD in technical chemistry from Vienna University of Technology, Vienna, Austria, in 2003, and his habilitation in chemical engineering from Vienna University of Technology, Vienna, Austria, in 2009. Dr. Lackner in docent at Vienna University of Technology, Vienna, Austria, Johannes Kepler University, Linz, Austria and Xidian University, Xi'An, China. Having founded six companies, Dr. Lackner has more than 15 years of professional experience in the polymer industry in various senior leadership positions in Austria and China. His research interests include biopolymers, in situ brownfield remediation technologies, process systems engineering, and industrial engineering. He has authored over 100 scientific publications. He is founding editor-in-chief of the *International Journal of Biobased Plastics*.



Dr. Baharak Sajjadi is an assistant professor of Petroleum and Geological Engineering in the Mewbourne College of Earth and Energy at the University of Oklahoma, USA. She has obtained her PhD in chemical engineering from the University of Malaya, Malaysia, in 2015, and has served as a research assistant professor of Chemical Engineering at the University of Mississippi, USA. She has over 10 years of research experience in advanced refinery processes and bioprocesses, carbon conversion and modification technologies, renewable energies, and computational fluid dynamics

(CFD simulation). Dr. Sajjadi has published over 50 scientific articles in peer-reviewed journals. She pioneered the use of ultrasound, non-thermal plasma, and chemical methods for carbon capture and conversion, natural gas conversion, and other environmental applications.

Dr. Wei-Yin Chen is a professor emeritus of Chemical Engineering of the University of Mississippi. He has had over 40-years of experience in developing technology-driven, knowledge-based, carbon conversion programs for in-furnace NO reduction, coal liquefaction, and low-temperature carbon modifications for sustainable food, energy, and water nexus. He founded and has been leading the Sustainable Energy and Environmental Group (SEEG) with over 250 collaborators around the globe. The SEEG pioneered the use of ultrasound, light, non-thermal plasma, biological, and chemical methods to modify the material surface for carbon gasification, carbon activation for CO_2 capture and wastewater treatment, soil amendment, electrode fabrication, desalination/deionization, biomedical material, fuel cell, etc. He has been awarded by UM and national and international organizations for his contributions to research, teaching, and services. He has served as a reviewer or panelist for institutions around the globe.

Dietary Manipulation to Mitigate Greenhouse Gas Emission from Livestock

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Abstract

The emission of greenhouse gases from livestock due to the fermentation process in the gastrointestinal tract is a colossal burden for veterinarians worldwide. These detrimental greenhouse gases are considered not only environmental pollutants but also toxic to human health. Livestock is considered a significant contributor to climate change by releasing these biogases into the ecosystem. In recent years, research has been focused on alteration of rumen microflora and fermentation kinetics of livestock for enhancing feed consumption and reducing the emission of toxic biogases. A plethora of supplements are being added into the feed of livestock for reducing the emission of greenhouse gases into the ecosystem. In this chapter, we have summarized the promising roles of probiotics, exogenous enzymes, plant metabolites and fodder trees, organic acids, and other microbes as ideal dietary feed additives for the sustainable mitigation of greenhouse gases release from ruminant and non-ruminant animals.

Keywords

Dietary supplements · Ecosystem · Feed · Greenhouse gases · Livestock · Mitigation

Introduction

Livestock alter the environment of the biosphere by producing greenhouse gases (GHG) through direct (enteric fermentation) or indirect (processing of feed and conversion of agroforestry into fodder) mechanisms. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the primary GHG produced by the livestock sector throughout the production process and cause global warming (Velázquez et al. 2020). The production of CO_2 from animals is not a net contributor towards changing the environment because livestock depends on plants for nutrition that utilize CO_2 for physiological processes (Steinfeld et al. 2006). On the other hand, CH_4 and N_2O are crucial greenhouse gases produced by livestock and contribute global warming effects (Solomon et al. 2007). Livestock contributes approximately 18% of the global anthropogenic greenhouse gas emission. In 2005, the global anthropogenic greenhouse gas productions from agricultural systems were about 6.2 gigatonnes CO_2-equivalent, animals sharing about 9% of it (IPCC 2007). In general, animals produce greenhouse gases as a by-product of the digestion mechanism, and these gases (particularly CH_4) get trapped in the atmosphere, causing global warming (Fig. 1).

Ruminants are the leading contributors to GHG, with approximately 80% of the entire sector's productions (Opio et al. 2013). On the other hand, non-ruminants contribute only about 9% of the sector's productions (Gerber et al. 2013). Similarly, small ruminants have lower contributions of about 8.5% (Opio et al. 2013). GHG

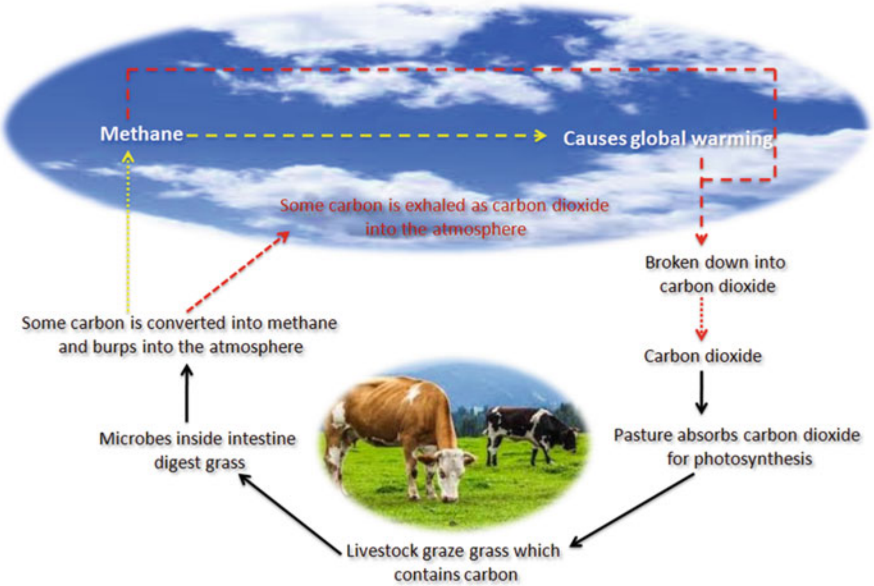

Fig. 1 Livestock produce greenhouse gases as by-product of digestion mechanism, and these gases are trapped in the atmosphere, causing climate change

emissions from livestock were calculated as 15% of all human-induced productions. Feed fermentation is the primary source of greenhouse gas productions, representing approximately 45% of the greenhouse gases of the entire agricultural sector. According to the US Environmental Protection Agency (EPA 2009), CH_4 release from enteric fermentation makes up 20% of overall CH_4 production from anthropogenic resources (EPA 2011). According to the EPA (2006), the non-CO_2 production from animals would be about 8% of the worldwide greenhouse gases produced in 2020.

The rapidly increasing human population will cause an increment in the global food demand which will certainly increase the demands for animal products. Therefore, the sector will compromise ecological sustainability. Hence, the cleaner and instantaneous greenhouse gas reduction approaches are paramount issues for reducing the greenhouse effect. The emission of greenhouse gases from livestock industries can be mitigated by manipulating their diet using distinct feed additives.

Brief on Greenhouse Gases Emissions

Greenhouse Gases Emissions in Agriculture

It has become a global concern due to its subsequent impacts on global climate. Agriculture, forestry, and land-use change account for 20.3 $GtCO_2e$ (Ahmed et al. 2020). It contributes to about 24% of global greenhouse gas emission (IPCC 2014).

These emissions come mainly from enteric fermentation, forestry and land-use change, rice cultivation, manure, on-farm energy use, synthetic fertilizer, burning savanna, global food waste, etc. (FAO 2006; FAO 2016; WRI 2018) which release CO_2, N_2O, and CH_4 into the atmosphere. Enteric fermentation is the most significant factor affecting greenhouse gases emissions from ruminants which account for about 30% of total CH_4 emission concomitantly resulting in a loss of about 2–12% of the dietary energy intake of animals (FAO 2020). Recently, it has been reported that agriculture greenhouse gases emissions have been increased from 71.6 to 174.6 Mt of CO_2-equivalent from 1994 to 2015, from which enteric emission contribute with 45.1% (Ijaz and Goheer 2020). Livestock farming impacts the environment, biodiversity, and ecosystem functionality through the consumption of finite resources (land, water, and energy) and production of physical flows (such as nutrients, greenhouse gases, and toxic substances) and also produces goods and services (European Union 2020). Globally, between 2005 and 2015, emission from agriculture increased by 8%, and regionally, Asia, Latin America and the Caribbean, Africa, Europe, North America, and Oceania contributed about 44%, 17%, 15%, 11%, 9%, and 4%, respectively, of the global 5246 kilotonne of CO_2-equivalent emissions from agriculture (FAOSTAT 2016). Eastern and Western Africa; Eastern, Southern, and Easter Asia; and southern America account for 62%, 73%, and 87% of agricultural emission in Africa, Asia, and Latin America and the Caribbean, respectively. Enteric fermentation, manure on pasture, synthetic fertilizer, paddy rice, manure management, and burning savannah account for 40%, 16%, 12%, 10%, 7%, and 5% of the global agricultural emitters (FAOSTAT 2016). In Latin America and the Caribbean, Africa, and Asia, livestock-related emission (enteric fermentation, manure left on pasture, manure management) accounts for the highest agricultural emissions of 86%, 69%, and 52%, respectively (FAO 2016).

Enteric Emission

Enteric fermentation is a biological process that occurs in the foregut or hindgut of livestock to ensure microbial breakdown of feed consumed, and this process leads to the production of many fermentation products including CH_4. Enteric fermentation remains the highest contributor to agricultural greenhouse gases emission in developing countries. In 2005–2014, enteric fermentation accounted for 59%, 39%, and 34% of agricultural emission in Latin America and the Caribbean, Africa, and Asia, respectively (FAOSTAT 2016). Enteric emission from 1990 to 2018 shows that there was a total of 1,939,090 gigagrams with Africa, America, Asia, Europe, and Oceania emitting 35.2%, 32.7%, 14.4%, 13.9%, and 3.8%, respectively (FAOSTAT 2018). Of the total enteric emission, 54.7%, 18.9%, 10.5%, 7%, 4.4%, and 4.5% are emitted by non-dairy cattle, dairy cattle, buffalos, sheep, goats, and horses, camels, asses, and swine combined (FAOSTAT 2018). FAO (2017) shows that 50% CH_4, 24% N_2O, and 26% CO_2 account for 50, 24, and 26% of emissions comes from the livestock sector. These facts highlight the need to reduce greenhouse gases emission from livestock. Despite the focus on the greenhouse gases emission from livestock, some authors have questioned the true impact of CH_4 from livestock on our environment (Allen et al. 2018; Raiten et al. 2020). This is based on the relative "life span" and bio-recycling of CO_2 by livestock (Cain 2018; Allen et al. 2018). It is known that the life span of CH_4 is less than a decade compared to CO_2 and N_2O with a longer life span ($\leq$1000 year) (Raiten et al. 2020). Thus, if ruminants do not increase, CH_4 emission from ruminant is bio-recycled because no new carbon is added to the atmosphere. This is because photosynthesis by plants converts carbon dioxide to plant-based carbohydrates (cellulose), and ruminants convert these forages into energy and high-quality protein, and in the process, CH_4 is produced. The CH_4 emitted during enteric fermentation and from manure lasts about a decade in the atmosphere and it is broken down into CO_2 and water. The CO_2 from the ruminants become a recycled one compared to CO_2 from other agricultural sectors and the fossil fuel industry (Raiten et al. 2020). Notwithstanding farmers in developing countries where emission intensity per kg of product is high and must continue to improve their animals' productivity in order to reduce the need to add more animals which will result in increased CH_4 emission. Adegbeye et al. (2020), Ahmed et al. (2020), and Frank et al. (2019) have all recommended expanded use of feed additives in global agriculture to reduce emission. Various dietary practices including use of feed additives, high-quality forages, and inclusion of ionophores have been employed to reduce CH_4 emanation in ruminants. Different additives such as probiotics, plant extracts, and essential oils have shown promising effect in terms of reducing greenhouse gases or redirection of hydrogen ions away from the methanogenesis (Hassan et al. 2020; Reddy et al. 2020).

Dietary Manipulation

Among various strategies for GHG mitigation, manipulation of diet is an ideal approach that not only improves animal's productivity but also reduces the production of GHG. The alteration of the diet can decrease CH_4 production up to 30% based on the extent of variation and the characteristic of the intercession (Benchaar et al. 2001). In another investigation, CH_4 emission decreased up to 70% by altering nutritional constituents (Mosier et al. 1998). Feeding altered diets not only improves the quality of forage but also directly target methanogenesis or change the metabolic mechanisms, causing the reduction of methanogenesis. Feed supplements such as organic acids, probiotics, exogenous enzymes, and plants or small fodder trees are incorporated into the diet to reduce the greenhouse gas emission from livestock (Fig. 2).

Organic Acids

Organic acids are promising feed supplements for reducing CH_4 and CO_2 emissions from livestock. Organic acids induce the formation of propionic acid in the rumen and, thus, decrease CH_4 emission (Castillo et al. 2004). Fumarate and acrylate reduce

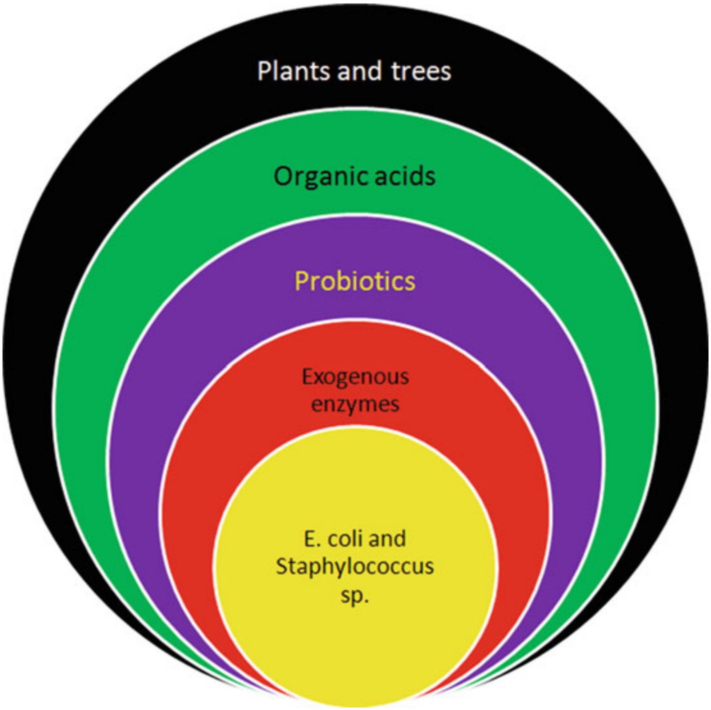

Fig. 2 Various important feed supplements incorporated into the diet to reduce greenhouse gases emission from farm animals

CH_4 productions in batch cultures, but fumarate is considered more efficient than acrylate (McAllister and Newbold 2008). The addition of propionate precursors in the diet reduced CH_4 production as the reductive pathways vary among organic acid sources (McAllister and Newbold 2008). An in vivo study in beef cattle exhibited a potent alteration in rumen fermentation by fumarate, although the mitigation of CH_4 production was not affected (Beauchemin and McGinn 2006). The addition of organic acid to the diet has been chiefly investigated for in vitro CH_4 and CO_2 production (Table 1).

Elghandour et al. (2016a) demonstrated the sustainable mitigation of CH_4 and CO_2 production by substituting dietary corn grain with soybean hulls in the presence of organic acid salts. The corn grain was substituted at three doses/kg dry matter (DM) 0 g (control), 75 g (soybean hulls), or 150 g (soybean hulls). The organic acid salt was also supplemented at three concentrations: 0, 5, and 10 mg/g dry matter of substrates. Results showed that soybean hulls at 75 and 150 g/kg DM reduced the asymptotic CO_2 production. The addition of soybean hulls and organic acid salt enhanced the production of CH_4. Similarly, the sustainable production of CH_4 and CO_2 by replacing corn grain with prickly pear cactus flour in the presence of different levels (0, 5, and 10 mg/g DM) of organic acid was also investigated. The

Table 1 Effect of organic acids on mitigation of greenhouse gas production

Organic acids	Doses/ dietary level	Animal species	Ingredient(s)-based diet	Impact on greenhouse gas production	References
Fumaric acid	175 g/kg	Angus heifers	75% whole-crop barley silage and 19% steam-rolled barley	No measurable reductions in CH_4 emissions	Beauchemin and McGinn (2006)
Organic acid salts	5 and 10 mg/g	Brown Swiss cow	Mixed rations	Decreased CO_2 and CH_4 emissions	Elghandour et al. (2016a)
Organic acid salts	5 and 10 mg/g	Brown Swiss cow	Mixed rations	Increased CO_2 emissions	Elghandour et al. (2016b)
Fumarate	20 and 30 mM	Goat	Mixed rations	Reduced CH_4 production	Asanuma et al. (1999)
Malate	4, 8, and 12 mM	Steer	6.8 kg of forage and 2.3 kg of concentrate	Reduction in CH_4 concentration	Martin and Streeter (1995)
Fumaric acid	80 g/kg	Cattle	75% whole crop barley silage, 19% steam-rolled barley, and 6% supplement	Mitigated CH_4 emission	McGinn et al. (2004)
3-Nitrooxypropanol	0–280 mg/ kg	Cows and sheep	High-forage diet	Decreased enteric CH_4 emissions per unit of body weight	Jayanegara et al. (2018)
Dimethyl-2-nitroglutarate and 2-nitro-methyl-propionate	2.97 or 11.88 μmol	Holstein-Friesian cow	High-concentrate diet	Produced >92% less CH_4	Anderson et al. (2010)
3-Nitrooxypropanol	17.8–7.18 g/kg	Holstein cows	High-forage diet	Reduced CH_4 emissions without compromising milk production	Haisan et al. (2014)
3-Nitrooxypropanol	0.75, 2.25, and 4.50 mg/kg	Angus heifers	60% barley silage, 35% barley grain, and 5% vitamin-mineral supplement	Reduced CH_4 production with 33% less CH_4 emission at the highest level of supplementation	Romero-Perez et al. (2014)

(continued)

Table 1 (continued)

Organic acids	Doses/ dietary level	Animal species	Ingredient(s)-based diet	Impact on greenhouse gas production	References
3-Nitrooxypropanol	2 g/kg	Angus heifers	60% barley silage, 35% barley grain, and 5% vitamin-mineral supplement	Sustained reduction in enteric CH_4 emissions	Romero-Perez et al. (2015)
3-Nitrooxypropanol	100–200 mg/kg	Beef cattle	High-forage and high-grain diets	Lowered total CH_4 emissions	Vyas et al. (2016)
Propionate precursors	592–612 g/kg	Sheep	Grass hay-concentrate (50:50, w/w) diet	Decreased CH_4 emissions	Newbold et al. (2005)
Fumarate	10–30 mM	–	Ryegrass pasture substrate	Reduced CH_4 output by 38% in continuous fermenters	Kolver et al. (2004)
Calcium propionate, malate, and monopropylene glycol	5 and 10 mg/g	Brown Swiss cow	Maize silage	Increased asymptomatic gas production	Elghandour et al. (2017a)

increase in prickly pear cactus level showed a linear effect on asymptotic gas CH_4 and CO_2 productions (Elghandour et al. 2016b).

Fumarate was used as a dietary supplement for the mitigation of CH_4 emission in the rumen. The supplementation of fumarate to the culture of mixed ruminal microbiota decreased CH_4 emission, suggesting that the inclusion of fumarate to ruminant feed decreased methanogenesis and improved propionate emission in the rumen (Asanuma et al. 1999). The impact of various doses of malate on in vitro mixed ruminal microbial fermentation of starch or cracked corn showed a significant reduction in CH_4 concentration (Martin and Streeter 1995).

Beauchemin and McGinn (2006) studied the effect of various feed additives on reduction of enteric CH_4 emissions from cattle. The feed additive reduced CH_4 productions by 32% which was mainly due to the reduced feed intake and lower DM digestibility. In contrast, the addition of fumaric acid into the diet showed no impact on CH_4 production. Findings revealed reduced emission of CH_4 from cattle due to the canola oil supplementation of canola oil. Essential oils and fumaric acid did not affect CH_4 emissions.

In another investigation, sunflower oil reduced CH_4 emission by 22% relative to the control. On the contrary, monensin and proteolytic enzymes did not influence biogas production group. Likewise, Procreatin 7 yeast, Levucell yeast, and fumaric acid showed no influence on CH_4 emission from steers. Findings revealed that sunflower oil, ionophores, and yeasts could be utilized to mitigate CH_4 emission from cattle (McGinn et al. 2004).

Jayanegara et al. (2018) demonstrated that the incorporation of 3-nitrooxy-propanol (3-NOP) at various concentrations reduced enteric CH_4 emission per unit of body weight and dry matter intake from ruminants. On the other hand, various doses of 3-NOP significantly increased hydrogen (H_2) production. Findings showed that 3-NOP is an effective dietary supplement to reduce the production of enteric CH_4 without altering the productive performance of ruminant. The effects of nitroethane, dimethyl-2-nitroglutarate, and 2-nitro-methyl-propionate were determined on in vitro ruminal CH_4 emission. Results showed a 92% CH_4 reduction with the use of nitrocompounds produced $>$92% less CH_4 than non-treated controls (Anderson et al. 2010).

The effect of 3-NOP supplementation to lactating Holstein cows on CH_4 emissions has been demonstrated. The inclusion of 3-NOP into the diet reduced CH_4 production from 17.8 to 7.2 g/kg DM intake. Findings indicated that supplementing 3-NOP to lactating dairy cows at 2500 mg/d can decrease CH_4 emission without affecting milk yield (Haisan et al. 2014). Similarly, Romero-Perez et al. (2014) evaluated the role of 3-NOP (0.75, 2.25, and 4.50 mg/kg body weight) for the reduction of enteric CH_4 emissions in beef cattle. Results showed a dose-dependent 3-NOP CH_4 reduction for the control. The use of 4.5 mg/kg body weight of 3-NOP in beef cattle reduced enteric CH_4 emissions without negatively affecting diet digestibility. In another investigation, the inclusion of 3-NOP into the feed reduced enteric CH_4 emission from cattle (Romero-Perez et al. 2015).

Data of Vyas et al. (2016) showed that the addition of NOP lowered total CH_4 emissions with the best response at 200 mg NOP/kg DM. For the high-grain diet, the emission of total CH_4 was reduced with increased doses of 3-NOP. Overall, these findings show that cattle fed high-forage and high-grain diets, along with 3-NOP/kg DM, decrease enteric CH_4 emission. Newbold et al. (2005) concluded that propionate precursors can reduce CH_4 up to 17%. Furthermore, fumarate (3.5 g/L) reduced CH_4 production by 38% in continuous fermenter using forage as potential substrate (Kolver et al. 2004). In contrast, Beauchemin and McGinn (2006) showed a lack of fumarate effect on CH_4 reduction. The addition of calcium propionate, malate, and monopropylene glycol into the feed of Brown Swiss cow showed an increment in asymptotic gas production (Elghandour et al. 2017a).

Probiotics

Probiotics are being exploited as dietary supplements to mitigate GHG productions from livestock. The specific mechanism for CH_4 reduction using probiotic microbes is not extensively studied due to the lack of successful incorporation of acetogens to the rumen (Lopez et al. 1999). In general, the ability of probiotics to influence fermentation in an animal depends on the dietary components. Table 2 illustrates the role of different probiotics as feed supplements to reduce GHG emissions from livestock. *Lactobacillus plantarum*, *L. casei*, *L. acidophilus*, *Enterococcus faecium*, *Selenomonas ruminantium*, *Megasphaera elsdenii*, *Saccharomyces cerevisiae*, and *Aspergillus oryzae* are widely used for improving animal's health (McAllister et al. 2011). Yeast cells are being utilized for improving rumen fermentation, DM intake, and milk yield (Beauchemin et al. 2008). Tsukahara et al. (2001) demonstrated a significant decrement in intestinal gas emission in pigs in the presence of lactic acid bacteria as feed additive. However, hydrogen sulfide emission was enhanced, and an adverse interaction between hydrogen sulfide and CH_4 emission took place. Takahashi et al. (2000) reported the influence of lactic acid bacteria on methanogenesis and observed an increment in biogases production. The impact of equine [Azteca horses' (aged 5–8 years, 480 ± 20.1 kg)] fecal inocula on in vitro CH_4 and CO_2 emission was elucidated by supplementing *L. farciminis* (Elghandour et al. 2018a). The incorporation of *L. farciminis* elevated asymptotic CH_4 and CO_2 emission.

The impact of fecal inocula from horses supplemented with *S. cerevisiae* in feed constituting oat straw on in vitro GHG production as indicator of hindgut activity was estimated by Elghandour et al. (2017b). Commercial *S. cerevisiae*, i.e., Biocell F53 (YST53), decreased CH_4 emission by 78%. In another study, three different commercial *S. cerevisiae* such as Biocell F53 (YST53), Procreatin 7 (YST07), and Biosaf SC47 (YST047) were tested to evaluate in vitro CH_4 and CO_2 production from horses. Results showed that YST53 supplementation at 4 mg/g DM decreased CH_4 emission. On the other hand, the inclusion of yeast products showed no significant effect on CO_2 production (Elghandour et al. 2016c). Likewise, the addition of *S. cerevisiae* into the diet enhanced CO_2 production from horses (Velázquez et al. 2016). *L. plantarum* MTD1 was co-administered with waste molasses for evaluating its effect on the silage quality, rumen volatile fatty acids, and GHG emissions. Findings showed that *L. plantarum* had no influence on CH_4

Table 2 Effect of probiotics on mitigation of greenhouse gas production

Microbial species	Doses/dietary level	Animal species	Ingredient (s)-based diet	Impact on greenhouse gas production	References
Lactobacillus acidophilus, *Bifidobacterium bifidum*, and *Enterococcus faecalis*	0.1 g/kg	Pigs	Corn meal and wheat, soybean meal, fish meal and defatted milk, and other components to contain total digestible nutrients	Decreased CO_2 emission. Negative correlation was seen between hydrogen sulfide and CH_4 production	Tsukahara et al. (2001)
Micrococcus, *Staphylococcus*, *Pediococcus*, *Leuconostoc*, *Paracoccus*, *Streptococcus*, *Lactobacillus*, *Gluconobacter*, and *Bacillus*	4 g/L	Cows	Bermuda grass hay	Increased total gas, CO_2, and CH_4 emission	Takahashi et al. (2000)
Lactobacillus farciminis	2, 4, and 6 mg/g	Azteca horses	Oat straw and a commercial concentrate	In vitro gas, CH_4, and CO_2 productions increased	Elghandour et al. (2018a)
S. cerevisiae	2 and 4 mg/g	Sheep	Mixed rations with high crude protein	Increased CH_4 productions	Elghandour et al. (2017b)
S. cerevisiae	2 and 4 mg/g	Horses	Mixed rations with high crude protein	Decreased CH_4 productions. No significant effect on CO_2 emission	Elghandour et al. (2016c)
S. cerevisiae	2 and 4 mg/g	Horses	Mixed rations with high crude protein	Increased CO_2 productions	Velázquez et al. (2016)
Lactobacillus plantarum	2 and 4%	Holstein cows	Rice straw	No effect on the mitigation of	Zhao et al. (2019)

(continued)

Table 2 (continued)

Microbial species	Doses/dietary level	Animal species	Ingredient (s)-based diet	Impact on greenhouse gas production	References
				CH_4 but decreased the CO_2 production	
Trichosporon sericeum and *Leuconostoc mesenteroides* subsp. *Mesenteroides*	1 and 4 g/kg	Sheep	40% timothy hay, 30% alfalfa hay cube, and 30% concentrate	Reduced CH_4 emission	Mwenya et al. (2004)
Paenibacillus	0.2%	Jersey cow	–	Reduced CH_4 emission	Latham et al. (2018)
S. cerevisiae	20–60 mg/g	Cow	Hay plus concentrate	Increased total gas production	Lila et al. (2006)
S. cerevisiae	2.5–7.5 g/kg	Goats	Cereal straws	Improved in vitro gas production	Tang et al. (2008)
S. cerevisiae	0.2 and 0.4 mg/g	Pigs	Corn-soybean basal diet	Suppressed in vitro CH_4 production	Gong et al. (2013)
S. cerevisiae	0.2 and 0.4 mg/g	Horses	Oat straw	Decreased CH_4 production	Salem et al. (2015)
Candida norvegensis	2×10^8 cfu	Cows	Oat straw	Reduced CH_4 production	Ruiz et al. (2016)

'–' = Not available

reduction but reduced CO_2 emission. Furthermore, the incorporation of waste molasses reduced CH_4 emission in a concentration-dependent manner (Zhao et al. 2019).

The addition of yeast culture (*Trichosporon sericeum*), lactic acid bacteria (*Leuconostoc mesenteroides* subsp. *Mesenteroides*), and β-1-4 galacto-oligosaccharides (GOS) on rumen methanogenesis in sheep reduced CH_4 production in GOS and yeast culture incorporated diets compared to control, suggesting that GOS and yeast culture inclusion could decrease CH_4 production in ruminants (Mwenya et al. 2004). Latham et al. (2018) demonstrated the effects of dietary nitrate and *Paenibacillus* 79R4 on CH_4 emissions in vitro. This study showed that 79R4 inoculation complemented the ruminal CH_4-decreasing potential.

Feeding hay plus concentrate with *S. cerevisiae* live cells enhanced in vitro biogas emission at different concentrations (Lila et al. 2006). Tang et al. (2008) also demonstrated that *S. cerevisiae* supplementation increased the gas production rate and total gas production. Gong et al. (2013) found a decreased total gas production rate from pigs offered yeast cultures. Lynch and Martin (2002) observed a reduction in CH_4 production using *S. cerevisiae* as feed additive. Salem et al. (2015) also reported that the inclusion of *S. cerevisiae* mitigated CH_4 production in horses. Likewise, in another study, Ruiz et al. (2016) demonstrated the influence of *Candida norvegensis* (yeast culture) on greenhouse gas production and revealed mitigation of CH_4 emission.

Exogenous Enzymes

Cellulase, xylanase, and hemicellulase are currently used in ruminant diets as feed additives. These enzymes can enhance fiber digestibility and animal productivity (Beauchemin et al. 2003). These enzymes also decrease the acetate/propionate ratio in the rumen, thus reducing CH_4 production (Eun and Beauchemin 2007). However, the supplementation of exogenous enzymes for reducing GHG produced from farm animals is very limited (Table 3).

Kholif et al. (2016) assessed the influence of fecal inocula from horses supplemented with fibrolytic enzymes and concluded that xylanase at 3-mL/g DM increased GHG productions. Arriola et al. (2011) demonstrated a significant decrease in enteric CH_4 emission from lactating cows offered fibrolytic enzymes. In another investigation, Biswas et al. (2016) found reduced CH_4 production due to lysozyme addition to the animal's diet. Hernandez et al. (2017a) found that the use of various doses of exogenous xylanase for calves reduced CH_4 and increased CO_2 productions, suggesting the efficient role of xylanases in diets for ruminants as a mean for a cleaner ecosystem.

Table 3 Effect of exogenous enzymes on mitigation of greenhouse gas production

Enzyme/s contents	Doses/ dietary level	Animal species	Ingredient (s)-based diet	Impact on greenhouse gas production	References
Endoglucanases and xylanases	1 unit/g	Holstein cows	Alfalfa hay	Reduction in CH_4 production	Eun and Beauchemin (2007)
Xylanase	1 and 3 μg/g	Horses	Concentrate and oat straw	Improved CH_4 production	Kholif et al. (2016)
Xylanase	3.4 mg/g	Holstein cows	Concentrate diet	Reduced enteric CH_4 emission	Arriola et al. (2011)
Lysozyme	2000–8000 unit	Holstein cows	Commercial concentrate to rice straw	Reduced CH_4 emission	Biswas et al. (2016)
Xylanase	3 and 6 μL/g	Calves	Concentrate diet	Increased CO_2 emission while reduced CH_4 production	Hernandez et al. (2017a)

Plant Metabolites and Fodder Trees

Plants possess diverse classes of secondary metabolites which can be exploited as feed ingredients as well as feed additives to mitigate the emission of GHG from livestock (Salem et al. 2014). Tree leaves and plant secondary metabolites are generally considered safe for modifying ruminal microbe's fermentative mechanism (Kholif et al. 2015). Various phytochemicals, viz., terpenoids, saponins, tannins, phenols, alkaloids, phenolic glycosides, essential oils, etc., modify the rumen fermentative process (Salem et al. 2015). The potentiality of plant-derived dietary supplements relies on types, sources, and levels of distinct bioactive metabolites (Elghandour et al. 2015). Plant secondary metabolites enhanced the feed digestibility because they enhance efficiency of rumen activity (Kholif et al. 2015). Extracts from leaves of diverse plants with increased flavonoids and tannins levels reduced CH_4 emission and increased microbiota counts (Broudiscou et al. 2002). Additionally, phenols and saponins are other important secondary metabolites capable of improving feed utilization efficiency and mitigate methanogenesis by suppressing rumen protozoa and bacteria (Dohme et al. 1999). The effect of various fodder trees and plant extracts on GHG production from animals is shown in Table 4.

In vitro and in vivo anti-methanogenic traits of tannin have been studied (Goel and Makkar 2012). Tannins inhibit ruminal microbiota (Bodas et al. 2012), and the supplementation of tannin-rich forages such as lucerne, sulla, red clover, chicory, and lotus to ruminants effectively reduce CH_4 emission (Ramirez-Restrepo and Barry 2005). Despite the CH_4 mitigating attributes of tannins, these phytoconstituents in large concentrations hamper forage digestibility and animal productivity, thereby restricting its use as a feed additive (Beauchemin et al. 2008). Saponins are naturally occurring surface-active glycosides present in diverse plant species that decrease CH_4 emission (Patra and Saxena 2009). Saponins are known to exhibit anti-protozoal characteristics by forming complex sterols in protozoa cell membranes (Goel and Makkar 2012) and possess antibacterial properties too (Moss et al. 2000). Saponins exhibit anti-protozoal properties at low concentration (Newbold et al. 1997), while higher concentration suppresses CH_4-producing microbes (Bodas et al. 2012). A 50% reduction of CH_4 production has been reported with saponins supplementation (Patra and Saxena 2009).

Elghandour et al. (2017c) demonstrated the reduction of CH_4 and CO_2 emission from calves supplemented with nine different tree leaves, with plant leaves showing significant asymptotic CH_4 emission (mL/g DM). Likewise, the asymptotic CO_2 emission was significantly reduced in the presence of various tree leaves. Pedraza-Hernandez et al. (2019) explored the reduction of CH_4 and CO_2 production from goats using *Moringa oleifera* extract as feed supplement. The asymptotic CH_4 production and rate of CH_4 emission were reduced using diverse concentrations of this feed additive. The proportional CH_4 and CO_2 production also decreased at higher concentrations of *M. oleifera* extract. These authors concluded that the supplementation of *M. oleifera* extract in diets would be a promising approach to mitigate CH_4 and CO_2 productions in goats.

Table 4 Effect of trees and plant extracts on mitigation of greenhouse gas production

Plant species	Major metabolite	Doses/dietary level	Animal species	Ingredient(s)-based diet	Impact on greenhouse gas production	References
Medicago sativa, *Pistacia vera*, *Dalbergia retusa*, *Crescentia alata*, *Azadirachta indica*, *Eichhornia crassipes*, *Cnidoscolus chayamansa*, *Guazuma ulmifolia*, *Vitex mollis*, and *Moringa oleifera*	Phenols and saponins	1 g/kg	Calves	Mixed ration	Reduced CH_4 and CO_2 productions	Elghandour et al. (2017c)
Moringa oleifera	–	0.6 and 1.8 mL/g	Goats	Oat straw, ground corn, soybean paste, urea, molasses, and sunflower oil	Decreased proportional CH_4 and CO_2 emission	Pedraza-Hernandez et al. (2019)
Andropogon gayanus, *Brachiaria ruziziensis*, *Pennisetum purpureum*, *Cajanus cajan*, *Cratylia argentea*, *Gliricidia sepium*, *Leucaena leucocephala*, *Stylosanthes guianensis*, *Annona senegalensis*, *Moringa oleifera*, *Securinega virosa*, and *Vitellaria paradoxa*	–	1 g/kg	Cows	Mixed ration	Reduced cumulative gas and CH_4 emission	Meale et al. (2012)

(continued)

Table 4 (continued)

Plant species	Major metabolite	Doses/dietary level	Animal species	Ingredient(s)-based diet	Impact on greenhouse gas production	References
Melia azedarach, *Ziziphus mucronata*, *Morus alba*, and *Rhus lancea*	Phenols and tannins	400 mg/g	Sheep	Mixed rations	Reduced CH_4 emission	Gemeda and Hassen (2015)
Rapeseed oil, safflower oil, and linseed oil	–	50 g/kg	Cows	Forage-to-concentrate (60:40) diet	Reduced ruminal CH_4 emission	Bayat et al. (2018)
Olive, sunflower, or linseed oils	–	6%	Sheep	High-concentrate mixed ration	Reduced CH_4 emission	Vargas et al. (2020)
Artemisia princeps var. Orientalis, *Allium sativum*, *Allium cepa*, *Zingiber officinale*, *Citrus unshiu*, and *Lonicera japonica*	–	20 mg/g	Holstein cow	High-concentrate ration	Decreased CH_4 emissions	Kim et al. (2012)
Litchi chinensis, *Melastoma malabathricum*, *Lagerstroemia speciosa*, *Terminalia chebula*, and *Syzygium cumini*	Tannins	200 mg/g	Holstein-Friesian crossbred bulls	Mixed ration comprising finger millet (*Eleusine coracana*) straw and commercial concentrate mixture	Reduced CH_4 emission	Baruah et al. (2018)
Origanum vulgare	–	500 g/kg	Cows	Basal diet	Reduced CH_4 production	Tekippe et al. (2012)
Eucalyptus citriodora	Oil	25–150 μL/g	Sheep	Mixed ration (50% roughage/50% concentrate)	Reduced CH_4 production	Sallam et al. (2009)

Camaldulensis	–	100 and 200 g/kg	Holstein Friesian non-dairy cows	Rice straw ad libitum, together with concentrate Rice straw with concentrate diet	Reduced CH_4 emission	Manh et al. (1997)
Thymus spp. and *Origanum* spp.	Oil	5–5000 mg/L	Cows	Forage-concentrate diet (60:40)	Reduced CH_4 emission	Castillejos et al. (2006)
Rapeseed, sunflower seed, and linseed	Oil	20 and 40%	Cows	Concentrate diet consisted of barley and soybean meal	Reduced CH_4 emission	Machmüller et al. (1998)
Canola oil, cod liver oil, and coconut oil	Oil	10%	Holstein steer	Grass hay or a 90%:10% wheat/hay mixture	Reduced CH_4 emission	Dong et al. (1997)
Coconut oil and garlic powder	–	7% coconut oil, 50 and 100 g of garlic extract	Buffaloes	Rice straw	Mitigated CH_4 emission	Kongmuna et al. (2011)
Sunflower oil	–	400 g/kg	Holstein steers	75% barley silage, 19% steam-rolled barley grain, and 6% supplement	Decreased CH_4 emissions	McGinn et al. 2004
Safflower and fish oils	–	2.4 and 4.8% v/w	Horses	Steam-rolled corn	Mitigated in vitro CH_4, CO_2, and H_2 emission	Velázquez et al. (2020)
Acacia concinna, seed pulp of *Terminalia chebula*, *Terminalia bellirica*, *Emblica officinalis*, and seed kernel of *Azadirachta indica*	Tannins	0.25 and 0.5 mL/g	Buffalo	Wheat straw and concentrate mixture in 1:1 ratio	Mitigated enteric CH_4 production	Patra et al. (2006)

(continued)

Table 4 (continued)

Plant species	Major metabolite	Doses/dietary level	Animal species	Ingredient(s)-based diet	Impact on greenhouse gas production	References
Schizochytrium microalgae and sunflower oil	–	1–5%	Holstein steers and Creole goats	Oat hay and concentrate diet	Mitigation of CH_4 and CO_2 emission	Elghandour et al. (2017d)
M. oleifera	Tannins and phenols	–	Holstein steers and Creole goats	Alfalfa hay, crushed yellow corn, soybean meal, and wheat bran	Decreased CH_4 emission but increased CO_2 production	Elghandour et al. (2017e)
Garlic oil	–	30–500 μL/g	Holstein dairy calves	Concentrate diet	Decreased CH_4 and CO_2 emission.	Hernandez et al. (2017)
M. oleifera	–	0.6, 1.2, and 1.8 mL/g	Holstein steers	Basal experimental diet containing oats, straw, soybean hulls, barley, wheat bran, corn gluten feed, molasses, and vitamin-mineral premix	Reduced CH_4 and CO_2 emission	Elghandour et al. (2018c)

M. oleifera	–	0.6, 1.2, and 1.8 mL/g	Holstein steers	Alfalfa hay and a commercial feed concentrate	Reduced CH_4 and CO_2 emission	Parra-Garcia et al. (2019)
M. oleifera	3,5-Bis (1,1-dimethylethyl)-phenol, kaempferol, moringyne, niazimicin, and tetradecanoic acid	–	Horses	–	Mitigation of CH_4 emission (in silico)	Khusro et al. (2020)
Rhubarb	9,10-Anthracenedione,1,8-dihydroxy-3-methyl, phthalic acid isobutyl octadecyl ester, and diisooctyl phthalate	–	Ruminants	–	Mitigation of CH_4 emission (in silico)	Arokiyaraj et al. (2019)

‘–’ = Not available

Several tropical grass species, leguminous shrub, and non-leguminous shrub were studied for estimating the rate of CH_4 emission from livestock. Cumulative gas and CH_4 emission using these forages varied significantly after 24 h. *B. ruziziensis* and *G. sepium* showed moderate rate of CH_4 emission (Meale et al. 2012). In another study, 19 tanniferous browse plants were tested as feed supplements for CH_4 mitigation. The ash, ether extract, non-fibrous carbohydrate, neutral detergent insoluble nitrogen, acid detergent insoluble nitrogen, and crude protein of plants were adversely correlated with CH_4 emission. On the contrary, the emission of CH_4 was positively correlated with neutral acid detergent fiber, cellulose, and hemicellulose. Tannin reduced CH_4 emission effectively (Gemeda and Hassen 2015).

Odongo et al. (2010) studied the impact of polyphenol-containing plants, phenolic acids, purified tannins, saponin-containing plants, and isolated saponin-enriched fractions on rumen CH_4 formation process. Cinnamic, caffeic, p-coumaric, and ferulic acids reduced CH_4 emission. The supplementation of purified chestnut and sumach tannins (hydrolyzable tannins) reduced the production of CH_4 significantly. However, mimosa and quebracho tannins did not reduce CH_4 emission. Inclusion of fenugreek and *Sesbania* to the hay decreased CH_4 production per unit of substrate degraded.

In another investigation, Bayat et al. (2018) demonstrated the reduction of CH_4 in the ruminal fluid due to the supplementation of plant essential oils (rapeseed oil, safflower oil, and linseed oil). Vargas et al. (2020) reported that the inclusion of plant oils (sunflower or linseed) in diets for ruminant had favorable impact on ruminal fermentation and reduced the emission of CH_4. Kim et al. (2012) evaluated the effects of extracts from *Artemisia princeps var. Orientalis*, *Allium sativum*, *Allium cepa*, *Zingiber officinale*, *Citrus unshiu*, and *Lonicera japonica* on CH_4 reduction in ruminants. Among those extracts, *A. sativum* extract reduced the emission of CH_4 by 20%. Other plant extracts also reduced CH_4 emissions (wormwood 8%, onion 16%, ginger 16.7%, mandarin orange 12%, honeysuckle 12.2%), but the effect was comparatively lower than that of *A. sativum* extract. *Litchi chinensis*, *Melastoma malabathricum*, *Lagerstroemia speciosa*, *Terminalia chebula*, and *Syzygium cumini* revealed their capacity to reduce CH_4 production in vitro; therefore, these plants could be used as additive in the animal diet to reduce CH_4 production (Baruah et al. 2018).

Tekippe et al. (2012) tested 100 essential oils and plants for their inhibition of methanogenesis. The essential oil from *Anethum graveolens*, *Lavandula latifolia*, and *Ocimum basilicum* as well as one plant (*Origanum vulgare*) showed reduced CH_4 production in vitro. Evans and Martin (2000) reported CH_4 mitigating potential of thymol at low concentration. Similarly, Sallam et al. (2009) and Manh et al. (1997) demonstrated reduced CH_4 production potential of eucalyptus oil. Castillejos et al. (2006) investigated CH_4 mitigating attributes of thyme (*Thymus* spp.) and oregano (*Origanum* spp.) oils. These authors suggested that the significant reduction of CH_4 production is mainly due to the antimicrobial trait of thymol against some rumen bacteria. Machmüller et al. (1998) reported the anti-protozoal role of coconut oil, thereby reducing the CH_4 emission. A similar finding was reported by Dong et al. (1997) who observed that coconut oil was effective as CH_4 inhibitor.

Kongmuna et al. (2011) observed that the inclusion of coconut oil along with *A. sativum* powder mitigated CH_4 emission by reducing total ruminal protozoal counts. In a different investigation, the addition of sunflower oil to cattle feed reduced CH_4 emissions (McGinn et al. 2004). Recently, Velázquez et al. (2020) found an in vitro positive synergistic effect of safflower and fish oil on mitigation of CH_4, CO_2, and H_2 emission in substrates from equines.

The methanol extract of *Terminalia chebula* showed significant reduction of CH_4 emission in vitro (Patra et al. 2006). Moreover, Goel and Makkar (2012) indicated that the anti-methanogenic effect of tannins is dependent on the concentrations of feed and presence of hydroxyl groups in their structure. These authors further summarized that hydrolyzable tannins inhibit rumen methanogens bacteria, while the condensed tannins inhibit fiber digestion. Singhal et al. (2007) demonstrated in vitro CH_4 mitigation of pulp powder of *Sapindus mukorossi*, *Acacia concinna*, *Madhuca indica*, *Albizia lebbeck*, and *Yucca schiagera.*

The inclusion of *Schizochytrium* microalgae and sunflower oil in diets of Holstein steers and Creole goats showed sustainable reduction of CH_4 and CO_2 emission (Elghandour et al. 2017d). In another report, the supplementation of *M. oleifera* leaves in the diet of Holstein steers and Creole goats decreased CH_4 emission but increased CO_2 production (Elghandour et al. 2017e). Findings of Hernandez et al. (2017b) showed that supplementation of *A. sativum* oil quadratically reduced CH_4 and CO_2 emission from dairy calves fed a high concentrate feed. Elghandour et al. (2018b) investigated the influence of *M. oleifera* leaf extract on the GHG emission in Holstein steers. A significant interaction between experimental diet and doses of *M. oleifera* leaf extract was reported with a reduction of CH_4 and CO_2 productions. The study suggested that the replacement of corn grain by pear cactus and the supplementation of *M. oleifera* leaves can be used to reduced production of GHG from ruminants. A similar in vitro study was carried out by Parra-Garcia et al. (2019) who concluded that the replacement of corn grain with soybean hulls and supplementing *M. oleifera* extract decreased GHG production and enhance feed digestibility.

Recent in silico studies predicted the methanogenesis inhibition attributes of medicinal plants by targeting methyl-coenzyme M reductase (MCR) receptor in horses. Methanogens are known to convert H_2 and CO_2 into CH_4 by the catalytic action of MCR via the methanogenesis pathway (Daly et al. 2001). Methyl-coenzyme M reductase reduces methyl-coenzyme M (methyl-CoM) [CH_3-S-CoM, 2-(methylthio)ethanesulfonate] with coenzyme B (CoB) (CoB-S-H, 7-thioheptanoyl-threoninephosphate) into CH_4 (Wongnate and Ragsdale 2015). Ellefson and Wolfe (1981) first characterized MCR as 300 kD protein of three different sub-units arranged in the form of $\alpha_2\beta_2\gamma_2$ configuration (Ermler et al. 1997).

Khusro et al. (2020) predicted the anti-methanogenic attributes of *M. oleifera*-associated phyocomponents by targeting MCR receptor in horses using in silico tools. Among diversified phytoconstituents, 3,5-bis(1,1-dimethylethyl)-phenol, kaempferol, moringyne, niazimicin, and tetradecanoic acid revealed satisfactory drug-likeness attributes. Further, in silico analyses of selected compounds against MCR receptor showed the maximum affinity of tetradecanoic acid against MCR with docking E-value of -142.98 kJ/mol, followed by -133.98 kJ/mol (niazimisin),

−110.36 kJ/mol (kaempferol), −93.72 kJ/mol (3,5-bis(1,1-dimethylethyl)-phenol), and −92.62 kJ/mol (moringyne). This research concluded that tetradecanoic acid may be used as a promising anti-methanogenic metabolite for developing effective CH_4 mitigating drugs by targeting methanogenesis. In another study, Arokiyaraj et al. (2019) depicted anti-methanogenic characteristics of Rhubarb compounds using in silico tools on MCR. Docking results successfully indicated minimum binding energy values of three components (9,10-anthracenedione,1,8-dihydroxy-3-methyl; phthalic acid isobutyl octadecyl ester; and diisooctyl phthalate) against the target protein MCR.

Essential Oils

Feed additives from natural sources are preferred as compared to synthetic or chemical additives, owing to their residue-free and environment-friendly nature, lack of antimicrobial resistance, and toxic side effects. Moreover, natural feed additives like essential oils can reduce methanogenesis by either directly inhibiting rumen archaea bacteria or altering rumen fermentation patterns by inhibiting fibrolytic bacteria to control the provision of metabolic hydrogen ions from volatile fatty acid production (Cobellis et al. 2016). Many feed additives exhibit promising effects on CH_4 mitigation under in vitro conditions, but they show little or no effect under in vivo conditions. This could be due to the adaptation of rumen microbes to feed additives such as essential oils. However, a decrease in the digestibility of fiber in response to treatment with essential oils is another serious issue as it reduces animal performance (Benchaar and Greathead 2011).

Essential oils have been used extensively in the food industry due to their aromatic and preservative properties. Mostly, these are extracted from different parts (leaves, fruits, seeds, roots, wood, and bark) of medicinal and aromatic plants, herbs, and spices. However, their concentration might vary due to various factors such as plant type, growth stage, and stress as well as agro-climatic conditions (light, temperature, humidity, soil type, and fertilizer application) (Hart et al. 2008). Major plants that are considered good sources of essential oils include oregano, garlic, dill, paprika, cassia, juniper, tea tree, anise, rosemary, clove, pine, thyme, ginger, black pepper, carrot, cinnamon, coriander, cumin, eucalyptus, and fennel (Benchaar and Greathead 2011; Ornaghi et al. 2020; Ashmawy et al. 2020). Various essential oils used in ruminants as feed additives are presented in Table 5. Generally, there are five major groups of essential oils which include monoterpene hydrocarbons (α-pinene, myrcene, p-cymene, limonene, and careen), oxygenated monoterpenes (4-carvomenthenol, terpineol, β-citronellol, citronellyl formate, isobornyl acetate, and geranyl acetate), sesquiterpene hydrocarbons (d-elemene, daucene, caryophyllene, bergamotene, sesquiphellandrene, farnesene, acoradiene, curcumene, selinene, β-bisabolene, and muurolene), oxygenated sesquiterpenes (caryophyllene oxide, carotol, daucol, and isocalamendiol), and diterpenes (camphorene). Notably, all essential oils have few chemical components; for instance, *Origanum* species contains 30% carvacrol and 27% thymol as their primary components (Table 5).

Table 5 Composition of major essential oils derived from plants

Botanical name of plant	Common name	Major essential oils	Individual essential oil percentage	References
Syzygium aromaticum	Clove	Eugenol	74.6	Alshaikh and Perveen (2017)
		Chavibetol	19.7	
		Caryophyllene	3.5	
Thymus vulgaris	Thyme	Thymol	55.35	Gedikoğlu et al. (2019)
		P-Cymene	11.79	
Thymbra spicata	Zahter	Carvacrol	68.20	Gedikoğlu et al. (2019)
		Γ-Terpinene	13.94	
Zingiber officinale	Ginger	A-Zingiberene	9.05	Imane et al. (2020)
		B-Bisabolene	5.40	
		A-Curcumene	5.4	
Piper nigrum	Black pepper	Δ-3-Carene	21.5	Lee et al. (2020)
		DL-limonene	18.8	
		Caryophyllene	17.2	
		2-β-Pinene	14.3	
		A-Pinene	9.2	
Daucus carota	Carrot	Carotol	44.68	Gaglio et al. (2017)
		B-Bisabolene	12.72	
		Isoelemicin	11.51	
Origanum vulgare	Oregano	Carvacrol	45.92	Morshedloo et al. (2018)
		P-Cymene	12.01	
		Carvacrol methyl ether	9.98	
		C-Terpinene	9.7	
		Thymol	3.69	
Allium sativum	Garlic	Diallyl trisulfide	45.9	Dziri et al. (2014)
		Diallyl disulfide	35.6	
		Methyl allyl trisulfide	10.4	

(continued)

Table 5 (continued)

Botanical name of plant	Common name	Major essential oils	Individual essential oil percentage	References
Capsicum annuum	Paprika	Carotol	52.3	Silva et al. (2013)
		(Z)-β-Ocimene	23.6	
		Menthol	13.2	
Juniperus communis	Juniper	Sabinene	40.1	Maurya et al. (2018)
		A-Pinene	7.2	
		Cis-sabinene hydrate	3.8	
Cinnamomum cassia	Cassia	Cinnamaldehyde	69.1	Chahbi et al. (2020)
		Methoxycinnamic acid	21.18	
		Benzyl alcohol	6.14	
		Benzyl benzoate	3.53	
Melaleuca alternifolia	Tea tree	A-Carene	17.41	Imane et al. (2020)
		A-Pinene	13.05	
		Terpinen-4-ol	13.17	
		Γ-Terpinene	10.06	
		B-Pinene	6.86	
Pimpinella anisum	Anise	Anethole	94.16	Öz et al. (2018)
		P-Allylanisole	2.77	
		Anisaldehyde	2.66	
Rosmarinus officinalis	Rosemary	A-Pinene	13.36	Imane et al. (2020)
		B-Pinene	14.06	
		Camphor	7.12	
		Caryophyllene	5.77	
Cinnamomum verum	Cinnamon	Eugenol	76.85	Božik et al. (2017)
		Benzyl benzoate	3.87	
		Caryophyllene	2.97	

Coriandrum sativum	Coriander	Linalool	67.8	Caputo et al. (2016)
		Camphor	5.0	
		Geranyl acetate	3.7	
Cuminum cyminum	Cumin	A-Pinene	18.8	Tahir et al. (2016)
		Limonene	6.06	
		Octanal	7.57	
		Geranyl acetate	6.85	
		A-Thujene	15.1	
		Cuminaldehyde	10.2	
Eucalyptus globulus	Eucalyptus	Eucalyptol	55.43	Kassahun and Feleke (2019)
		A-Pinene	25.55	
		D-Limonene	5.69	
Foeniculum vulgare	Fennel	Trans-anethole	74.88	Kalleli et al. (2019)
		L-Fenchone	11.01	
		Limonene	4.67	
Cymbopogon winterianus	Lemon	Linalool	10.97	Imane et al. (2020)
		(R)-(+)-Citronellal	7.69	
		Linalyl anthranilate	3.24	
Anethum graveolens	Dill	Dillapiole	34.7	Singh et al. (2017)
		Oleic acid	21.2	
		Carvone	15.2	

A reduction of 36% and 40% in CH_4 production was observed with supplementation of 17.3 and 16.6 g of oregano per kg DM, respectively, in cattle (Hristov et al. 2013; Tekippe et al. 2011; Besharati et al. 2020). Oregano essential oils supplementation at the rate of 52, 91, and 130 mg/L in vitro decreased linearly CH_4 emission by 9.7, 14.9, and 11.2%, respectively (Zhou et al. 2020). Similarly, in vitro application of blends of essential oil active compounds at 600 and 1000 mg/L decreased CH_4 by 5.7 and 17.1%, respectively (Joch et al. 2019). Different sources of essential oils have been used in ruminant nutrition. For example, *Lippia turbinata* and *Tagetes minuta* have shown a tenfold decrease in CH_4 yield (in vitro) causing also alteration of nitrogen metabolism in the rumen (Garcia et al. 2019). Different plant essentials oils (origanum, garlic, and peppermint oils) have decreased abundance of *Firmicutes* and CH_4 production while increasing *Bacteroidetes* in the rumen (Patra and Yu 2015; Elghandour et al. 2018e). Similarly, cinnamon and cumin powder and their essential oils decreased in vitro ruminal gas, NH_3-N concentration, and CH_4 production (Jahani-Azizabadi et al. 2009, 2011).

Recently, Garcia et al. (2020) revealed that the chemical composition of essential oils, especially the proportion of oxygenated compounds, showed a positive interaction with fermentation pattern and promising effect regarding the reduction of essential oil mitigation. Recently a meta-analysis has shown that a blend of essential oils exhibited promising effects in dairy cattle via increasing milk yield (3.6%), milk fat and protein (4.1%), and feed efficiency (4.4%) while decreasing DM intake (12.9%) and CH_4 production (8.8%) during a long-term in vivo trial (Lin et al. 2013). This reveals the promising potential of plant essential oils to increase milk yield in dairy animals while mitigating CH_4 emission. Contrarily, few studies showed that oregano and caraway essential oils did not reduce CH_4 yield together with no effect on animal performance and rumen fermentation (Lejonklev et al. 2016; Olijhoek et al. 2019; Benchaar 2020). However, oregano essential oils have shown to improve the growth performance of calves (Wu et al. 2020).

Different essential oils inhibit NH_3-producing bacteria (*Prevotella* spp. and *R. amylophilus*) up to 77% in sheep. The reduction of NH_3 by plant essential oils has been extensively reported (Lin et al. 2013; Patra and Yu 2015; Cobellis et al. 2016). This reveals the ability of essential oils to inhibit proteolysis, peptidolysis, and deamination of amino acids (Patra 2011). Contrarily, an increase in the relative abundance of *Prevotella* species (*P. bryantii* and *P. ruminicola*) in response to the supplementation of higher levels of plant essential oils has also been reported (McIntosh et al. 2003). These divergent findings may be partially explained by variable experimental conditions of studies including the type of diets, plant species, dose and type of essential oils, pH of rumen fluid, and host animal.

Studies have suggested the use of a combination of different essential oils as a better strategy to modulate rumen microbiome to manipulate rumen fermentation than using individual essential oils, mainly because each essential oils possess complex mixture of phytochemicals and their synergistic effects can lead to synthesis of new compounds with pretty different bioactivity that could not be collected with individual compounds (McIntosh et al. 2003). Additionally, using a combination of phytochemicals is also advantageous for host regarding provision of various phytonutrients from different plant combinations. Moreover, benefits of such combination are its ultimate utility for using on a large scale in the animal industry as a commercial feed additive to have an overall impact on improvement of global animal production while mitigating greenhouse gases emissions (Table 6).

Rumen microbes are essential for ruminant productivity, feed digestion, and animal health. Their activity also influences the quality of animal products derived as well as the quantity of greenhouse gases produced by each animal. Their diversity ensures rumen ecosystem stability and enhances their adaptation to varying dietary strategies, and some help to cope with these changes by alternating metabolic pathways (Edwards et al. 2008). Both synthetic and herbal are used to alter the microbial activities. Rumen microbes include bacteria, protozoa, fungi, archaea, and bacteriophages with various diversities in phylum and genus (Faniyi et al. 2019). Dietary oil supplementation can shape the rumen microbial community (Lillis et al. 2011) because they contain unsaturated fatty acids which can modulate the ruminal activities with a negative effect on protozoa and fibrolytic bacteria growth (Enjalbert et al. 2017). Furthermore, the addition of oil to the diet of ruminants especially those with strong antimicrobial activity such as thymol and carvacrol (Burt 2004; Castillejos et al. 2006) affect microbial activity in the rumen with more negative impact on gram-positive than gram-negative bacteria due to the sensitivity of the former (Smith-Palmer et al. 1998). Essential oils and their active components can modify ruminal fermentation and energy use efficiency, decrease CH_4 emissions (Joch et al. 2016), and alter the ruminal bacterial community (Zhou et al. 2020), and some have shown no impact on rumen fermentation metabolites (Tekippe et al. 2013) nor elicit any microbial diversity (Schären et al. 2017). This varying effect of essential oil in rumen ecosystem activities suggests different adaptation responses. This may be due to shifts in microbial populations, microbial adaptation due to degradation of the bioactive ingredients (Gladine et al. 2007; Benchaar and Greathead 2011), or inadequate quantity of essential oil of eliciting any response (Zhou et al. 2020). The improvement in lactobacilli and *Dialister* suggests their impact on rumen biohydrogenation (Patra and Yu 2015) which could also influence the proportion of fatty acid profile in ruminant products. It also suggests how oregano oil might be influencing the fatty acid profile of animal products through microbial manipulation. A commercial essential oil CinnaGar (blend of cinnamaldehyde and garlic oil) supplemented at 0.0043% DM decreased total protozoa by 33% and increased entodinium protozoa by 3.2% in continuous culture (Ye et al. 2018). The decrease in protozoa may influence the reduction in CH_4 production (Patra 2011) because of their close relationship with methanogens (Newbold et al. 2015; Kim et al. 2019). This result is contrary to the non-specific antimicrobial activity of essential oil against bacteria, protozoa, and fungi (Cobellis et al. 2016). Rumen ciliate protozoa have been known to exhibit fibrolytic activity (Koike and Kobayashi 2009), and the fungi in the rumen have also been considered to produce fibrolytic enzymes (Yang et al. 2007; Giannenas et al. 2011). In sheep, oregano essential oil supplementation at the rate of 4 and 7 g/day showed varied effects on microbial population. Ewes supplemented with 4 g/day improved total bacteria population – *R. flavefaciens*, *R. albus*, and *F. succinogenes* – while 7 g/day

Table 6 Essential oils derived from plants and their impact on greenhouse gases emission from livestock

Botanical name	Common name	Animal species	Impact on greenhouse gases	References
Origanum vulgare	Oregano	Cattle	Decreased CH_4 output	Hristov et al. (2013); Tekippe et al. (2011)
Lippia turbinata and *Tagetes minuta*	NA	In vitro	Tenfold decrease in CH_4	Garcia et al. (2019)
Caraway (*Carum carvi*) and oregano (*Origanum vulgare*)	Oregano and caraway	In vivo	Reduced CH_4	Lejonklev et al. (2016); Olijhoek et al. (2019); Benchaar (2020)
NA	Blend of essential oil	In vitro	Reduced CH_4 output	Joch et al. (2019)

NA: Not available

essential oil significantly improved fungi population (Zhou et al. 2019). The above in vitro and in vivo studies showed that cellulolytic microbes and fungi tend to have good adaption to different essential oils, which enable them to proliferate. The seemingly positive effect on cellulolytic bacteria indicates that essential oil may not have a bactericidal effect, suggesting that essential oil can aid fiber degradation in ruminants. It could also be summarized that dosage of essential oil will affect the response that can be obtained from their use and its effect on greenhouse gases emission, animal performance, and animal product quality (Table 7).

Interaction Between Diets and Other Bacteria (*Escherichia coli* and *Staphylococcus* sp.)

Elghandour et al. (2018c) evaluated the effect of *E. coli* (10, 20, and 40 mg/g DM of substrates) against rumen microbes' fermentative properties in the reduction of GHG emission by changing dietary corn grain with prickly pear cactus flour. Results showed significant reduction of asymptotic CH_4 production at 10 and 20 mg/g DM of *E. coli*. Further, the asymptotic CO_2 emission was significantly reduced using various doses of pear cactus and *E. coli*. In another study, Elghandour et al. (2018d) showed that the addition of *E. coli* to soybean hulls-based diets mitigated asymptotic CO_2 emission in sheep. However, the additive revealed no significant effect on CH_4 production.

García et al. (2019) investigated the effectiveness of ensiled devil fish (DF) and *Staphylococcus saprophyticus* supplementation on GHG emission reduction traits in horses. Various doses of DF (%) at 0 (control DF0), 6 (DF6), 12 (DF12), and 18 (DF18), as well as three doses of *S. saprophyticus* (0, 1, and 3 mL/g DM), were added to the feed. The supplementation of DF18 showed the lowest production of CO_2. On the other hand, the lowest emission of H_2 was observed in DF0, whereas DF18 exhibited the maximum production. The addition of DF12 and DF18 mitigated CH_4 production by 58.2 and 59.3%, respectively. However, DF, *S. saprophyticus*, and DF × *S. saprophyticus* interaction revealed no significant influence on CH_4 emission. Thus, ensiled DF and *S. saprophyticus* can be used as ideal feed supplements to mitigate the production of GHG in equines.

Conclusion and Future Perspectives

The livestock sector is considered a significant producer of GHG such as CH_4, CO_2, H_2, and N_2O which lead to global warming. The urgency to mitigate the emission of detrimental GHG from farm animals has encouraged the researchers to find propitious alternatives. To enhance the efficacy of GHG mitigation, the utilization of diverse plant extracts, microbes, and enzymes as dietary supplements in ruminants and non-ruminants has shown promising alternatives.

Supplementation of feed additives such as probiotics, exogenous enzymes, medicinal plants and leaves of certain trees, organic acids, and other microbes

Table 7 Essential oils derived from plants and their impact on ruminal microbial adaptation

Common name	Major essential oils	Animal species	Adaptation impact to EO	References
Oregano essential oil	Carvacrol	In vitro	Improved microbial (*Prevotella*, *Succiniclasticum, Lactobacillus, Firmicutes*, *Bacteroidetes*, *Proteobacteria,* and *Dialister)* growth	Zhou et al. (2020)
Commercial essential oil CinnaGar	Blend of cinnamaldehyde and garlic oil	Continuous culture system	Decreased total protozoa and increased entodinium protozoa	Ye et al. (2018)
Essential oil mixture	Cinnamaldehyde, thymol, and eugenol	In vitro	Increased protozoa, fungi and cellulolytic bacteria growth	Kim et al. (2019)
Commercial essential oil (Crina Ruminants)	NA	Chios dairy ewes	Improved cellulolytic bacteria growth	Giannenas et al. (2011)
Oregano essential oils	NA	Ewes	Improved total bacteria population; improved fungi population, and decreased protozoa	Zhou et al. (2019)

NA: Not available

offer a viable and effective role for significant mitigation of GHG emission from horses, sheep, goats, and cows while maintaining their productivity. Studies have revealed that a blend of various essential oils has a promising effect in terms of better performance and reduction of CH_4 production. However, fewer studies also have shown undesirable effects of essential oils on feed digestibility and animal performance. Such contradictory findings may be attributed to rumen microbial diversity, quantity and type of diet, and type of essential oils. Application of essential oils could have a multi-benefit impact in ruminant diet by reducing greenhouse gases.

These feed additives may be utilized as quintessential supplements in the feed of disparate animals and can control economic aspects of the livestock industries. In a nutshell, the manipulation of diet by supplementing diversified non-toxic additives at proper concentration would be an ideal strategy to reduce GHG emissions of GHG from farm animals to maintain a cleaner ecosystem. However, further in-depth in vivo experiments are still essential to understand the interaction between the effective components of dietary additives and livestock systems for detecting the most effective and practical biogas mitigation approaches.

Cross-References

▶ Ruminant Productivity Among Smallholders in a Changing Climate: Adaptation Strategies

References

Adegbeye MJ, Ravi Kanth Reddy P, Obaisi AI, et al (2020) Sustainable agriculture options for production, greenhouse gasses and pollution alleviation, and nutrient recycling in emerging and transitional nations – an overview. J Clean Prod 242:118319

Ahmed J, Almeida E, Aminetzah D, et al (2020) Agriculture and climate change. Reducing emissions through improved farming practices, McKinsey and Company, pp 1–45

Allen MR, Shine KP, Fuglestvedt JS et al (2018) A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. NPJ Clim Atmos Sci 1:16

Alshaikh N, Perveen K (2017) Anti-candidal activity and chemical composition of essential oil of clove (Syzygiumaromaticum). J Essen Oil Bear Plants 20(4):951–958

Anderson RC, Huwe JK, Smith DJ et al (2010) Effect of nitroethane, dimethyl-2-nitroglutarate and 2-nitro-methyl-propionate on ruminal methane production and hydrogen balance *in vitro*. Bioresour Technol 101:5345–5349

Arokiyaraj S, Stalin A, Shin H (2019) Anti-methanogenic effect of rhubarb (*Rheum* spp.) – an *in silico* docking studies on methyl-coenzyme M reductase (MCR). Saudi J Biol Sci 26:1458–1462

Arriola KG, Kim SC, Staples CR et al (2011) Effect of fibrolytic enzyme application to low-and high-concentrate diets on the performance of lactating dairy cattle. J Dairy Sci 94:832–841

Asanuma N, Iwamoto M, Hino T (1999) Effect of the addition of fumarate on methane production by ruminal microorganisms *in vitro*. J Dairy Sci 82:780–787

Ashmawy NA, Farraj DA, Salem MZM et al (2020) Potential impact of *Pinus halepensis* Miller trees as a source of phytochemical compounds: antibacterial activity of the cones essential oil and n-butanol extract. Agrofor Syst 94:1403–1413

Baruah L, Malik PK, Kolte AP et al (2018) Methane mitigation potential of phyto-sources from Northeast India and their effect on rumen fermentation characteristics and protozoa *in vitro*. Vet World 11:809–818

Bayat AR, Tapio I, Vilkki J et al (2018) Plant oil supplements reduce methane emissions and improve milk fatty acid composition in dairy cows fed grass silage-based diets without affecting milk yield. J Dairy Sci 101:1136–1151

Beauchemin K, McGinn S (2006) Methane emission from beef cattle: effects of fumaric acid, essential oil and canola oil. J Anim Sci 84:1489–1496

Beauchemin KA, Colombatto D, Morgavi DP et al (2003) Use of exogenous fibrolytic enzymes to improve feed utilization by ruminants. J Anim Sci 81:E37–E47

Beauchemin KA, Kreuzer M, O'Mara F et al (2008) Nutritional management for enteric methane abatement: a review. Aust J Exp Agric 48:21–27

Benchaar C (2020) Feeding oregano oil and its main component carvacrol does not affect ruminal fermentation, nutrient utilization, methane emissions, milk production, or milk fatty acid composition of dairy cows. J Dairy Sci 103(2):1516–1527

Benchaar C, Greathead H (2011) Essential oils and opportunities to mitigate enteric methane emissions from ruminants. Anim Feed Sci Technol 166:338–355

Benchaar C, Pomar C, Chiquette J (2001) Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. Can J Anim Sci 81:563–574

Besharati M, Moaddab V, Nemati Z et al (2020) Influence of cinnamon essential oil and monensin on the ruminal biogas kinetic of waste pomegranate seeds as a biofriendly agriculture environment. Waste Biomass Valoriz. https://doi.org/10.1007/s12649-020-01167-2

Biswas AA, Lee SS, Mamuad LL et al (2016) Use of lysozyme as a feed additive on *in vitro* rumen fermentation and methane emission. Asian Aust J Anim Sci 29:1601–1607

Bodas R, Prieto N, García-González R et al (2012) Manipulation of rumen fermentation and methane production with plant secondary metabolites. Anim Feed Sci Technol 176:78–93

Božik M, Nový P, Klouček P (2017) Chemical composition and antimicrobial activity of cinnamon, thyme, oregano and clove essential oils against plant pathogenic bacteria. Acta Univ Agric Silvic Mendelianae Brun 65(4):129–1134

Broudiscou LP, Papon Y, Broudiscou AF (2002) Effects of dry plant extracts on feed degradation and the production of rumen microbial biomass in a dual outflow fermenter. Anim Feed Sci Technol 101:183–189

Burt S (2004) Essential oils: their antibacterial properties and potential applications in foods – a review. Int J Food Microbiol 94:223–253. https://doi.org/10.1016/j.ijfoodmicro.2004.03.022

Cain M (2018) Guest post: a new way to assess "global warming potential" of shortlived pollutants. [Internet]. CarbonBrief, London; c2018. Accessed 5 Dec 2019. Available from: https://www.carbonbrief.org/guestpost-a-new-way-to-assess-global-warming-potential-of-short-livedpollutants

Caputo L, Souza LF, Alloisio S et al (2016) Coriandrum sativum and *Lavandula angustifolia* essential oils: chemical composition and activity on central nervous system. Int J Mol Sci 17(12):1999

Castillejos L, Calsamiglia S, Ferret A (2006) Effect of essential oil active compounds on rumen microbial fermentation and nutrient flow in *in vitro* systems. J Dairy Sci 89:2649–2658

Castillo C, Benedito JL, Mendez J et al (2004) Organic acids as a substitute for monensin in diets for beef cattle. Anim Feed Sci Technol 115:101–116

Chahbi A, Nassik S, El Amri H et al (2020) Chemical composition and antimicrobial activity of the essential oils of two aromatic plants cultivated in Morocco (Cinnamomum cassia and Origanum compactum). J Chem 10. Article ID 1628710. https://doi.org/10.1155/2020/1628710

Cobellis G, Trabalza-Marinucci M, Marcotullio MC (2016) Evaluation of different essential oils in modulating methane and ammonia production, rumen fermentation, and rumen bacteria in vitro. Anim Feed Sci Technol 215:25–36

Daly K, Stewart CS, Flint HJ et al (2001) Bacterial diversity within the equine large intestine as revealed by molecular analysis of cloned 16S rRNA genes. FEMS Microbiol Ecol 38:141–151

Dohme F, Machmuller A, Estermann BL et al (1999) The role of the rumen ciliate protozoa for methane suppression caused by coconut oil. Lett Appl Microbiol 29:187–192

Dong Y, Bae HD, McAllister TA et al (1997) Lipid induced depression of methane production and digestibility in the artificial rumen system. Can J Anim Sci 77:269–278

Dziri S, Casabianca H, Hanchi B et al (2014) Composition of garlic essential oil (*Allium sativum* L.) as influenced by drying method. J Essent Oil Res 26(2):91–96

Edwards JE, Huws SA, Kim EJ et al (2008) Advances in microbial ecosystem concepts and their consequences for ruminant agriculture. Animals 2:653–660

Elghandour MMY, Kholif AE, Bastida AZ et al (2015) *In vitro* gas production of five rations of different maize silage and concentrate ratios influenced by increasing levels of chemically characterized extract of *Salix babylonica*. Turk J Vet Anim Sci 39:186–194

Elghandour MMY, Kholif AE, Salem AZM et al (2016a) Addressing sustainable ruminal methane and carbon dioxide emissions of soybean hulls by organic acid salts. J Clean Prod 135:194–200

Elghandour MMY, Kholif AE, Salem AZM et al (2016b) Sustainable anaerobic rumen methane and carbon dioxide productions from prickly pear cactus flour by organic acid salts addition. J Clean Prod 139:1362–1369

Elghandour MMY, Kholif AE, López S et al (2016c) In vitro gas, methane, and carbon dioxide productions of high fibrous diet incubated with fecal inocula from horses in response to the supplementation with different live yeast additives. J Equine Vet Sci 38:64–71

Elghandour MMY, Kholif AE, Hernandez A et al (2017a) Effects of organic acid salts on ruminal biogas production and fermentation kinetics of total mixed rations with different maize silage to concentrate ratios. J Clean Prod 147:523–530

Elghandour MMY, Vázquez JC, Salem AZM et al (2017b) *In vitro* gas and methane production of two mixed rations influenced by three different cultures of *Saccharomyces cerevisiae*. J Appl Anim Res 45:385–395

Elghandour MMY, Salem AZM, Khusro A et al (2017c) Assessment of some browse tree leaves on gas production and sustainable mitigation of CH_4 and CO_2 emissions in dairy calves at different age. J Clean Prod 162:1192–1199

Elghandour MMY, Vallejo LH, Salem AZM et al (2017d) Effects of *Schizochytrium* microalgae and sunflower oil as sources of unsaturated fatty acids for the sustainable mitigation of ruminal biogases methane and carbon dioxide. J Clean Prod 168:1389–1397

Elghandour MMY, Vallejo LH, Salem AZM et al (2017e) *Moringa oleifera* leaf meal as an environmental friendly protein source for ruminants: biomethane and carbon dioxide production, and fermentation characteristics. J Clean Prod 165:1229–1238

Elghandour MMY, Khusro A, Greiner R et al (2018a) Horse fecal methane and carbon dioxide production and fermentation kinetics influenced by *Lactobacillus farciminis*-supplemented diet. J Equine Vet Sci 62:98–101

Elghandour MMY, Rodríguez-Ocampo I, Parra-Garcia A et al (2018b) Biogas production from prickly pear cactus containing diets supplemented with *Moringa oleifera* leaf extract for a cleaner environmental livestock production. J Clean Prod 185:547–553

Elghandour MMMY, Khusro A, Salem AZM et al (2018c) Role of dose dependent *Escherichia coli* as ruminal anti-microflora agent to mitigate biogases production in prickly pear cactus flour based diet. Microb Pathog 115:208–215

Elghandour MMMY, Antolin-Cera X, Salem AZM et al (2018d) Influence of *Escherichia coli* inclusion and soybean hulls based diets on ruminal biomethane and carbon dioxide productions in sheep. J Clean Prod 192:766–774

Elghandour MM, Salem MZM, Greiner R et al (2018e) Effect of natural blends of garlic and eucalyptus essential oils on biogas production of four fibrous feed at short term incubation in the ruminal anaerobic biosystem. J Sci Food Agric 98:5313–5321

Ellefson WL, Wolfe RS (1981) Component C of the Methyl reductase system of Methanobacterium. J Biol Chem 256:4259–4262

Enjalbert F, Combes S, Zened A et al (2017) Rumen microbiota and dietary fat: a mutual shaping. J Appl Microbiol 123:782–797

EPA (2006) Global mitigation of non-CO_2 gases. Environmental Protection Agency (EPA), Washington, DC

EPA (2011) Greenhouse gas emissions and sinks. Environmental Protection Agency (EPA), Washington, DC

Ermler U, Grabarse W, Shima S et al (1997) Crystal structure of Methyl–coenzyme M reductase: the key enzyme of biological methane formation. Science 278:1457–1462

Eun JS, Beauchemin KA (2007) Assessment of the efficacy of varying experimental exogenous fibrolytic enzymes using *in vitro* fermentation characteristics. Anim Feed Sci Technol 132:298–315

European Union (2020) Study on Future of EU livestock: how to contribute to a sustainable agricultural sector? Final report. Publications Office of the European Union, Luxembourg, pp 1–82. https://doi.org/10.2762/3440

Evans JD, Martin SA (2000) Effects of thymol on ruminal microorganisms. Curr Microbiol 41:336–340

Faniyi TO, Adegbeye MJ, Elghandour MMY et al (2019) Role of diverse fermentative factors towards microbial community shift in ruminants. J Appl Microbiol 127:2–11

FAO (2006) Livestock's long shadow. Environmental issues and options food and agriculture organization of the United Nations, Rome, Italy

FAO (2016) FAO's work on climate change GHG emission. Greenhouse Gas Emissions from Agriculture, Forestry and Other Land Use. www.fao.org/climate-change

FAO (2017) Global Livestock Environmental Assessment Model (GLEAM). FAO, Rome. 109pp. www.fao.org/gleam/en/

FAO (2020) Reducing Enteric Methane for improving food security and livelihoods. http://www.fao.org/in-action/enteric-methane/background/what-is-enteric-methane/en/

Food and Agriculture Organization of the United Nation (2016) FAOSTAT. http://www.fao.org/faostat/en/#compare. Accessed Jan 2021

Food and Agriculture Organization of the United Nation (2018) FAOSTAT. http://www.fao.org/faostat/en/#compare. Accessed Jan 2021

Frank S, Havlík P, Stehfest E et al (2019) Agricultural non-CO_2 emission reduction potential in the context of the 1.5 °C target. Nat Clim Chang 9:66–72

Gaglio R, Barbera M, Aleo A et al (2017) Inhibitory activity and chemical characterization of *Daucus carota subsp. maximus* essential oils. Chem Biodivers 14(5):e1600477

García EDA, Khusro A, Pacheco EBF et al (2019) Influence of dietary supplementation of ensiled devil fish and *Staphylococcus saprophyticus* on equine fecal greenhouse gases production. J Equine Vet Sci 79:105–112

Garcia F, Vercoe PE, Martínez MJ et al (2019) Essential oils from Lippia turbinata and Tagetes minuta persistently reduce in vitro ruminal methane production in a continuous-culture system. Anim Prod Sci 59(4):709–720

Garcia F, Colombatto D, Brunetti MA et al (2020) The reduction of methane production in the in vitro ruminal fermentation of different substrates is linked with the chemical composition of the essential oil. Animals 10(5):786

Gedikoğlu A, Sökmen M, Çivit A (2019) Evaluation of Thymus vulgaris and Thymbra spicata essential oils and plant extracts for chemical composition, antioxidant, and antimicrobial properties. Food Sci Nutr 7(5):1704–1714

Gemeda BS, Hassen A (2015) Effect of tannin and species variation on *in vitro* digestibility, gas, and methane production of tropical browse plants. Asian Aust J Anim Sci 28:188–199

Gerber PJ, Steinfeld H, Henderson B et al (2013) Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome

Giannenas I, Skoufos J, Giannakopoulos C et al (2011) Effects of essential oils on milk production, milk composition, and rumen microbiota in Chios dairy ewes. J Dairy Sci 94:5569–5577

Gladine C, Rock E, Morand C et al (2007) Bioavailability and antioxidant capacity of plant extracts rich in polyphenols, given as a single acute dose, in sheep made highly susceptible to lipoperoxidation. Br J Nutr 98:691–701

Goel G, Makkar HP (2012) Methane mitigation from ruminants using tannins and saponins. Trop Anim Health Prod 44:729–739

Gong YL, Liao XD, Liang JB et al (2013) *Saccharomyces cerevisiae* live cells decreased *in vitro* methane production in intestinal content of pigs. Asian Aust J Anim Sci 26:856–863

Haisan J, Sun Y, Guan LL et al (2014) The effects of feeding 3-nitrooxypropanol on methane emissions and productivity of Holstein cows in mid lactation. J Dairy Sci 97:3110–3119

Hart KJ, Yanez-Ruiz DR, Duval SM et al (2008) Plant extracts to manipulate rumen fermentation. Anim Feed Sci Technol 147:8–35

Hassan F, Arshad MA, Ebeid HM et al (2020) Phytogenic additives can modulate rumen microbiome to mediate fermentation kinetics and methanogenesis through exploiting diet- microbe interaction. Front Vet Sci 7:575801

Hernandez A, Kholif AE, Elghandour MMMY et al (2017a) Effectiveness of xylanase and *Saccharomyces cerevisiae* as feed additives on gas emissions from agricultural calf farms. J Clean Prod 148:616–623

Hernandez A, Kholif AE, Lugo-Coyote R et al (2017b) The effect of garlic oil, xylanase enzyme and yeast on biomethane and carbon dioxide production from 60-d old Holstein dairy calves fed a high concentrate diet. J Clean Prod 142:2384–2392

Hristov AN, Lee C, Cassidy T et al (2013) Effect of *Origanum vulgare* L. leaves on rumen fermentation, production, and milk fatty acid composition in lactating dairy cows. J Dairy Sci 96(2):1189–1202

Ijaz M, Goheer MA (2020) Emission profile of Pakistan's agriculture: past trends and future projections. Environ Dev Sustain. https://doi.org/10.1007/s10668-020-00645-w

Imane NI, Fouzia H, Azzahra LF et al (2020) Chemical composition, antibacterial and antioxidant activities of some essential oils against multidrug resistant bacteria. Eur J Integr Med 35:101074

IPCC (2007) Climate Change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change [Core Writing Team, Pachauri RK, Reisinger A (eds)]. IPCC, Geneva, Switzerland, 52 pp. Available at: www.ipcc.ch

IPCC (2014) Climate change 2014: mitigation of climate change. In: Edenhofer et al (eds) Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK/New York

Jahani-Azizabadi H, Danesh Mesgaran M, Vakili AR et al (2009) Screening the activity of medicinal plants or spices on in vitro ruminal methane production. J Dairy Sci 92:277–278

Jahani-Azizabadi H, Danesh Mesgaran M, Vakili A et al (2011) Effect of various medicinal plant essential oils obtained from semi-arid climate on rumen fermentation characteristics of a high forage diet using in vitro batch culture. Afr J Microbiol Res 5(27):4812–4819

Jayanegara A, Sarwono KA, Kondo M et al (2018) Use of 3-nitrooxypropanol as feed additive for mitigating enteric methane emissions from ruminants: a meta-analysis. Ital J Anim Sci 17:650–656

Joch M, Cermak L, Hakl J et al (2016) *In vitro* screening of essential oil active compounds for manipulation of rumen fermentation and methane mitigation. Asian Aust J Anim Sci 29:952. https://doi.org/10.5713/ajas.15.0474

Joch M, Kudrna V, Hakl J et al (2019) *In vitro* and *in vivo* potential of a blend of essential oil compounds to improve rumen fermentation and performance of dairy cows. Anim Feed Sci Technol 251:176–186

Kalleli F, BettaiebRebey I, Wannes WA et al (2019) Chemical composition and antioxidant potential of essential oil and methanol extract from Tunisian and French fennel (*Foeniculum vulgare* Mill.) seeds. J Food Biochem 43(8):e12935

Kassahun A, Feleke G (2019) Chemical composition and physico-chemical analysis of *Eucalyptus Globulus* leave and oil. Sci J Chem 7(2):36

Kholif AE, Gouda GA, Morsy TA et al (2015) *Moringa oleifera* leaf meal as a protein source in lactating goat's diets: feed intake, digestibility, ruminal fermentation, milk yield and composition, and its fatty acids profile. Small Rumin Res 129:129–137

Kholif AE, Baza-García LA, Elghandour MMY et al (2016) *In vitro* assessment of fecal inocula from horses fed on high-fiber diets with fibrolytic enzymes addition on gas, methane, and carbon dioxide productions as indicators of hindgut activity. J Equine Vet Sci 39:44–50

Khusro A, Aarti C, Salem AZM et al (2020) Methyl-coenzyme M reductase (MCR) receptor as potential drug target for inhibiting methanogenesis in horses using *Moringa oleifera* L.: an *in silico* docking study. J Equine Vet Sci 88:102949. https://doi.org/10.1016/j.jevs.2020.102949

Kim ET, Kim CH, Min KS et al (2012) Effects of plant extracts on microbial population, methane emission and ruminal fermentation characteristics in *in vitro*. Asian Australas J Anim Sci 25:806–811

Kim H, Jung E, Lee HG et al (2019) Essential oil mixture on rumen fermentation and microbial community – an in vitro study. Asian Australas J Anim Sci 32(6):808–814

Koike S, Kobayashi Y (2009) Fibrolytic rumen bacteria: their ecology and functions. Asian Australas J Anim Sci 22:131–138

Kolver ES, Aspin PW, Jarvis GN et al (2004) Fumarate reduces methane production from pasture fermented in continuous culture. In: Proceedings of the New Zealand society of animal production: New Zealand Society of Animal Production 64:155–159

Kongmuna P, Wanapat M, Pakdeea P et al (2011) Manipulation of rumen fermentation and ecology of swamp buffalo by coconut oil and garlic powder supplementation. Livest Sci 135:84–92

Latham EA, Pinchak WE, Trachsel J et al (2018) Isolation, characterization and strain selection of a *Paenibacillus* species for use as a probiotic to aid in ruminal methane mitigation, nitrate/nitrite detoxification and food safety. Bioresour Technol 263:358–364

Lee JG, Chae Y, Shin Y et al (2020) Chemical composition and antioxidant capacity of black pepper pericarp. Appl Biol Chem 63:35. https://doi.org/10.1186/s13765-020-00521-1

Lejonklev J, Kidmose U, Jensen S et al (2016) Effect of oregano and caraway essential oils on the production and flavor of cow milk. J Dairy Sci 99:7898–7903

Lila ZA, Mohammed N, Takahashi T et al (2006) Increase of ruminal fiber digestion by cellobiose and a twin strain of *Saccharomyces cerevisiae* live cells *in vitro*. Anim Sci J 77:407–413

Lillis L, Boots B, Kenny DA et al (2011) The effect of dietary concentrate and soya oil inclusion on microbial diversity in the rumen of cattle. J Appl Microbiol 111:1426–1435

Lin B, Lu Y, Salem AZM et al (2013) Effect of essential oil combination on sheep ruminal fermentation and digestibility of a diet with fumarate included. Anim Feed Sci Technol 184:24–32

Lopez S, McIntosh E, Wallace RJ et al (1999) Effect of adding acetogenic bacteria on methane production by mixed rumen microorganisms. Anim Feed Sci Technol 78:1–9

Lynch H, Martin S (2002) Effects of *Saccharomyces cerevisiae* culture and *Saccharomyces cerevisiae* live cells on *in vitro* mixed ruminal microorganism fermentation. J Dairy Sci 85:2603–2608

Machmüller AD, Ossowski A, Wanner M et al (1998) Potential of various fatty feeds to reduce methane release from rumen fermentation *in vitro*. Anim Feed Sci Technol 71:117–130

Manh NS, Wanapat M, Uriyapongson S et al (1997) Effect of eucalyptus (*Camaldulensis*) leaf meal powder on rumen fermentation characteristics in cattle fed on rice straw. Afr J Agric Res 7:1997–2003

Martin SA, Streeter MN (1995) Effect of malate on *in vitro* mixed ruminal microorganism fermentation. J Anim Sci 73:2141–2145

Maurya AK, Devi R, Kumar A et al (2018) Chemical composition, cytotoxic and antibacterial activities of essential oils of cultivated clones of Juniperus communis and wild Juniperus species. Chem Biodivers 15(9):e1800183

McAllister TA, Newbold CJ (2008) Redirecting rumen fermentation to reduce methanogenesis. Aust J Exp Agric 48:7–13

McAllister TA, Beauchemin KA, Alazzeh AY et al (2011) Review: the use of direct fed microbials to mitigate pathogens and enhance production in cattle. Can J Anim Sci 91:193–211

McGinn SM, Beauchemin KA, Coates T et al (2004) Methane emissions from beef cattle: effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. J Anim Sci 82:3346–3356

McIntosh F, Williams P, Losa R et al (2003) Effects of essential oils on ruminal microorganisms and their protein metabolism. Appl Environ Microbiol 69(8):5011–5014

Meale SJ, Chaves AV, Baah J (2012) Methane production of different forages in *In vitro* ruminal fermentation. Asian Aust J Anim Sci 25:86–91

Morshedloo MR, Mumivand H, Craker LE et al (2018) Chemical composition and antioxidant activity of essential oils in *Origanum vulgare subsp. gracile* at different phenological stages and plant parts. J Food Process Preserv 42(2):e13516

Mosier AR, Duxbury JM, Freney JR et al (1998) Mitigating agricultural emissions of methane. Clim Chang 40:39–80

Moss AR, Jouany JP, Newbold J (2000) Methane production by ruminants: its contribution to global warming. Ann Zootech 49:231–253

Mwenya B, Santoso B, Sar C et al (2004) Effects of including β1–4 galacto-oligosaccharides, lactic acid bacteria or yeast culture on methanogenesis as well as energy and nitrogen metabolism in sheep. Anim Feed Sci Technol 115:313–326

Newbold CJ, el Hassan SM, Wang J et al (1997) Influence of foliage from african multipurpose trees on activity of rumen protozoa and bacteria. Br J Nutr 78:237–249

Newbold CJ, Lopez S, Nelson N et al (2005) Propionate precursors and other metabolic intermediates as possible alternative electron acceptors to methanogenesis in ruminal fermentation *in vitro*. Br J Nutr 94:27–35

Newbold CJ, de la Fuente G, Belanche A et al (2015) The role of ciliate protozoa in the rumen. Front Microbiol 6:1313

Odongo NE, Garcia M, Viljoen GJ (2010) Sustainable improvement of animal production and health. Food and Agriculture Organization of the United Nations, Rome, pp 151–157

Olijhoek DW, Hellwing ALF, Grevsen K et al (2019) Effect of dried oregano (*Origanum vulgare* L.) plant material in feed on methane production, rumen fermentation, nutrient digestibility, and milk fatty acid composition in dairy cows. J Dairy Sci 102(11):9902–9918

Opio C, Gerber P, Mottet A et al (2013) Greenhouse gas emissions from ruminant supply chains – a global life cycle assessment. Food and Agriculture Organization of the United Nations (FAO), Rome

Ornaghi MG, Guerrero A, Vital ACP et al (2020) Improvements in the quality of meat from beef cattle fed natural additives. Meat Sci 163:108059

Öz E, Koç S, Çinbilgel İ et al (2018) Chemical composition and larvicidal activity of essential oils from *Nepeta cadmea Boiss*. and *Pimpinella anisum* L. on the larvae of *Culex pipiens* L. Marmara Pharm J 22(2):322–327

Patra AK (2011) Effects of essential oils on rumen fermentation, microbial ecology and ruminant production. Asian J Anim Vet Adv 6:416–428

Patra AK, Saxena J (2009) The effect and mode of action of saponins on the microbial populations and fermentation in the rumen and ruminant production. Nutr Res Rev 22:204–219

Patra AK, Yu Z (2015) Essential oils affect populations of some rumen bacteria in vitro as revealed by microarray (Rumen-BactArray) analysis. Front Microbiol 6:297. https://doi.org/10.3389/fmicb.2015.00297

Patra AK, Kamra DN, Agrawal N (2006) Effect of plant extracts on *in vitro* methanogenesis enzyme activities and fermentation of feed in the rumen liquor of buffalo. Anim Feed Sci Technol 128:276–291

Pedraza-Hernandez J, Elghandour MMMY, Khusro A et al (2019) Mitigation of ruminal biogases production from goats using *Moringa oleifera* extract and live yeast culture for a cleaner agriculture environment. J Clean Prod 234:779–786

Raiten DJ, Allen LH, Slavin JL et al (2020) Understanding the intersection of climate/environmental change, health, agriculture, and improved nutrition: A case study on micronutrient nutrition and animal source foods. Curr Dev Nutr 4:nzaa087

Ramirez-Restrepo CA, Barry TN (2005) Alternative temperate forages containing secondary compounds for improving sustainable productivity in grazing ruminants. Anim Feed Sci Technol 120:179–201

Reddy PRK, Elghandour MM, Salem AZM et al (2020) Plant secondary metabolites as feed additives in calves for antimicrobial stewardship. Anim Feed Sci Technol 264:114469

Romero-Perez A, Okine EK, McGinn SM et al (2014) The potential of 3-nitrooxypropanol to lower enteric methane emissions from beef cattle. J Anim Sci 92:4682–4693

Romero-Perez A, Okine EK, McGinn SM et al (2015) Sustained reduction in methane production from long-term addition of 3-nitrooxypropanol to a beef cattle diet. J Anim Sci 93:1780–1791

Ruiz O, Castillo Y, Arzola C et al (2016) Effects of *Candida norvegensis* live cells on *in vitro* oat straw rumen fermentation. Asian Aust J Anim Sci 29:211–218

Salem AZM, Kholif AE, Elghandour MM (2014) Effect of increasing levels of seven tree species extracts added to a high concentrate diet on *in vitro* rumen gas output. Anim Sci J 85:853–860

Salem AZM, Elghandour MMY, Chagoyán JCV et al (2015) The effect of live yeast (*Saccharomyces cerevisiae*) on *in-vitro* total gas, methane and carbon dioxide production of diet containing 50% oat straw in horses. J Fisheries Livest Prod 3:64–71

Sallam SMA, Bueno ICS, Brigide P et al (2009) Efficacy of eucalyptus oil on *in vitro* rumen fermentation and methane production. Options Méditérr 85:267–272

Schären M, Drong C, Kiri K et al (2017) Differential effects of monensin and a blend of essential oils on rumen microbiota composition of transition dairy cows. J Dairy Sci 100:2765–2783

Silva LR, Azevedo J, Pereira MJ et al (2013) Chemical assessment and antioxidant capacity of pepper (*Capsicum annuum* L.) seeds. Food Chem Toxicol 53:240–248

Singh S, Das SS, Singh G et al (2017) Comparative studies of chemical composition, antioxidant and antimicrobial potentials of essential oils and oleoresins obtained from seeds and leaves of *Anethum graveolens* L. Toxicol Open Access 3(119):2–9

Singhal K, Anamika K, Singh B (2007) Effect of saponins of plant extracts on rumen fermentation and methane emission. In: Proceedings of International animal Nutrition Conference, National Dairy Research Institute, Karnal 2, 297

Smith-Palmer A, Stewart J, Fyfe L (1998) Antimicrobial properties of plant essential oils and essences against five important food-borne pathogens. Lett Appl Microbiol 26:118–122

Solomon S, Qin D, Manning M (2007) Technical summary. In: Solomon S, Qin D, Manning M, Marquis M, Averyt K, MMB T, Miller HL, Chen ZL (eds) Climate change 2007. The physical science basis. Contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK/New York, pp 19–91

Steinfeld H, Gerber P, Wassenaar T et al (2006) Livestock's long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations (FAO), Rome

Tahir HU, Sarfraz RA, Ashraf A et al (2016) Chemical composition and antidiabetic activity of essential oils obtained from two spices (*Syzygium aromaticum* and *Cuminum cyminum*). Int J Food Prop 19(10):2156–2164

Takahashi J, Miyagawa T, Kojima Y et al (2000) Effects of *Yucca schidigera* extract, probiotics, monensin and L-cysteine on rumen methanogenesis. Asian Aust J Anim Sci 13:499–501

Tang SX, Tayo GO, Tan ZL et al (2008) Effects of yeast culture and fibrolytic enzyme supplementation on *in vitro* fermentation characteristics of low-quality cereal straws. J Anim Sci 86: 1164–1172

Tekippe JA, Hristov AN, Heyler KS et al (2011) Rumen fermentation and production effects of *Origanum vulgare* L. in lactating dairy cows. J Dairy Sci 94:5065–5079

Tekippe JA, Hristov AN, Heyler KS et al (2012) Effects of plants and essential oils on ruminal in vitro batch culture methane production and fermentation. Can J Anim Sci 92:395–408

Tekippe JA, Tacoma R, Hristov AN et al (2013) Effect of essential oils on ruminal fermentation and lactation performance of dairy cows. J Dairy Sci 96:7892–7903

Tsukahara T, Azuma Y, Ushida K (2001) The effect of a mixture of live lactic acid bacteria on intestinal gas production in pigs. Microb Ecol Health Dis 13:105–110

Vargas JE, Andrés S, López-Ferreras L et al (2020) Dietary supplemental plant oils reduce methanogenesis from anaerobic microbial fermentation in the rumen. Sci Rep 10:1613. https://doi.org/10.1038/s41598-020-58401-z

Velázquez AE, Kholif AE, Elghandour MMY et al (2016) Effect of partial replacement of steam rolled corn with soybean hulls or prickly pear cactus in the horse's diet in the presence of live *Saccharomyces cerevisiae* on *in vitro* fecal gas production. J Equine Vet Sci 42:94–101

Velázquez AE, Salem AZM, Khusro A et al (2020) Sustainable mitigation of fecal greenhouse gases emission from equine using safflower and fish oils in combination with live yeast culture as additives towards a cleaner ecosystem. J Clean Prod 256:120460. https://doi.org/10.1016/j.jclepro.2020.120460

Vyas D, McGinn SM, Duval S et al (2016) Optimal dose of 3-nitrooxypropanol for decreasing enteric methane emissions from beef cattle fed high-forage and high-grain diets. Anim Prod Sci 58:1049–1055

Wongnate T, Ragsdale SW (2015) The reaction mechanism of Methyl-coenzyme M reductase. J Biol Chem 290:9322–9334

World Resource Institute (2018) Creating a sustainable food future: synthesis report. https://www.wri.org/our-work/project/world-resources-report/publications

Wu J, Guo J, Liu T et al (2020) Feeding a calf starter containing monensin alone or in combination with an oregano, prebiotics, and cobalt blend to Holstein calves. J Anim Sci 98. https://doi.org/10.1093/jas/skaa214

Yang WZ, Benchaar C, Ametaj BN et al (2007) Effects of garlic and juniper berry essential oils on ruminal fermentation and on the site and extent of digestion in lactating cows. J Dairy Sci 90:5671–5681

Ye D, Karnati SKR, Wagner B et al (2018) Essential oil and monensin affect ruminal fermentation and the protozoal population in continuous culture. J Dairy Sci 101:5069–5081

Zhao J, Dong Z, Li J et al (2019) Evaluation of *Lactobacillus plantarum* MTD1 and waste molasses as fermentation modifier to increase silage quality and reduce ruminal greenhouse gas emissions of rice straw. Sci Total Environ 688:143–152

Zhou R, Wu J, Zhang L et al (2019) Effects of oregano essential oil on the ruminal pH and microbial population of sheep. PLoS One 14(5):e0217054

Zhou R, Wu J, Lang X et al (2020) Effects of oregano essential oil on in vitro ruminal fermentation, methane production, and ruminal microbial community. J Dairy Sci 103:2303–2314. https://doi.org/10.3168/jds.2019-16611