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Review

Sustainable Strategies for Greenhouse Gas Emission Reduction in Small Ruminants Farming

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Abstract: During the previous decades, the growing demand for animal origin products has gained considerable attention. As a result, livestock breeding has faced a rapid intensification in order to fulfil market expectations. This increase in livestock production has led to a large scale of manure that is associated with many environmental impacts, such as climate change, to an increase of greenhouse gases (GHG) emissions. Livestock production is considered to generate significant amounts of GHG, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Methane and nitrous oxide are the main emissions from livestock systems. Ruminants contribute highly to total livestock emissions. In the present study, the contribution of livestock and especially of the small ruminants in GHG emissions is reviewed. Additionally, useful sustainable strategies for farming and feeding of small ruminants are highlighted. Some of the practices discussed include but are not limited to efficient manure management, the replacement of mineral fertilizers by farm manure, the improvement of feed efficiency and provision of feed supplements. Moreover, the use of food waste or agro-industrial by-products is discussed as a sustainable strategy.

Keywords: agro-industrial by-products; farming; food waste; greenhouse gas emissions; small ruminants; sustainability; sustainable strategies

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1. Introduction

In 2022 around 8 billion people are estimated to live on Earth, while in 2050 this number is expected to be 10.4 billion [1]. Nutritional demands are going to rise in order to satisfy human needs. Meanwhile, the increasing human population in accordance with urbanization will alter the dietary habits to more processed rather than natural origin products. As a result, a large quantity of animal origin products will be necessary, putting pressure on the food market [2]. Until 2050, around two times the amount of milk and meat that is produced nowadays will be necessary to cover human needs; for instance, 1077 million tons of milk should be produced compared to the 580 tons that are produced today [3]. In order to meet this demand, livestock farming grows constantly. However, there are many concerns about the environmental impact of this intensified animal production [4]. The generation of greenhouse gas emissions (GHG) is the most important environmental impact as far as livestock farming is concerned. As the emissions from livestock increase, many changes concerning the atmosphere, the land and the oceans are occurring that lead to climate change.

Agriculture, and therefore livestock, is concurrently one of the main contributors to GHG emissions and consequently to climate change [5]. The significant amounts of GHG emissions are produced either through their physiological processes or during the production of animal origin products. The livestock sector is responsible for 14.5% of total anthropogenic GHG emissions, or 7.1 Gt CO2e [6]. Of this total, the share of feed production and processing is approximately 45% or 3.2 Gt CO_2e, the share of enteric fermentation is approximately 39% or 2.8 Gt CO_2e, and the share of manure management is approximately 10% or 0.71 Gt. The processing and transportation of animal products account for the remaining 6% or 0.42 Gt CO_2e. [6]. On the other hand, by accounting only for the direct CH_4 and N_2O emissions from enteric fermentation, manure management and distribution, the contribution is estimated to be 5.4 Gt CO_2e [6,7]. In EU, a report by Perez Dominguez et al. [8] indicates that agriculture accounts for 10.3% of total GHG emissions, with CH_4 from enteric fermentation accounting for 32% and manure management contributing another 16%. Cattle production is the largest contributor to global livestock emissions, contributing 4.6Gt CO_2e or 61%, while other species contribute much less: pigs 0.7 Gt CO_2e (9%), poultry 0.7 Gt CO_2e (8%) and small ruminants 0.474 Gt CO_2e (6%) [6,7].

An adequate level of reduction in GHG emissions by 2050 can be achieved, with selected strategies including but not limited to policies, infrastructures and technology in order to change human habits and behavior [9]. Agriculture could mitigate related emissions. The era of climate denial is over, human being is the main contributor of climate change and livestock farming could help reduce its footprint. Mitigation strategies need to be adopted in the livestock sector to reduce the environmental impact.

This review aimed to demonstrate the contribution of livestock and especially small ruminants in the climate change through its GHG emissions. It should be mentioned that for research purposes cattle literature will be used when appropriate in the following parts, since GHG mitigation strategies for small ruminants are sparse. Moreover, mitigation techniques that would provide a sustainable approach for the emissions' reduction concerning feed, energy and manure are explained. Additionally, the inclusion of food waste and agro-industrial by-products in ruminant diets are discussed as a circular bioeconomy leverage which can improve livestock sustainability.

2. Contribution of Small Ruminants to GHG

Small ruminants' contribution to GHG emissions are about 475 million tons CO_2e, which represents about 6.5% of the agriculture sector global emissions [7]. Sheep and goat world meat and milk production accounts for around 254 and 175 million tons CO_2e, respectively [7]. Small ruminants' milk production contributes about 12% of the total GHG emissions that come from CH_4 from enteric fermentation and manure and 19% from the N_2O of manure management [10]. The global average of GHG emission intensity of milk is lower for goats than for sheep with 5.2 and 8.4 kg CO_2e/kg product, respectively, mainly because goats have higher milk yields on average at the global level [7]. The GHG emission intensity of meat is very similar between the two species at about 23 kg CO_2e/kg meat [7].

Different geographical regions and production systems have different carbon footprints [7]. The term "carbon footprint" (CF) refers to the sum of greenhouse gas emissions and removals in a product system related to the climate change and associated with any human activity (e.g., livestock, domestic energy combustion, etc.) [11]. In extensive systems, the CF of goat milk is high while in semi-intensive and intensive systems, emissions per kg of milk are low [12–14] because of the high productivity and the high amount of compound feed used in the rations [13]. In the extensive, semi-intensive and intensive farms, methane from milk production accounts for 75%, 65% and 52% of total emissions, respectively [13]. More specifically, emission intensities for sheep and goat milk production ranged from 1.6 kg to 14.2 kg of CO_2e (in humid grassland areas of Western Europe and arid grassland areas of North Africa, respectively), while emission intensities for lamb and goat meat production ranged from 7.4 kg to 57.5 kg of CO_2e (in mixed areas of Western Europe and temperate grassland areas of North Africa, respectively) [7]. Nevertheless, to accurately develop mitigation options for the small ruminant farms, it is important to detect all potential sources of GHG emissions. The three 'greenhouse gases' (GHG) which contribute most to global warming are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [15]. The contribution of small ruminants is presented in Figure 1.

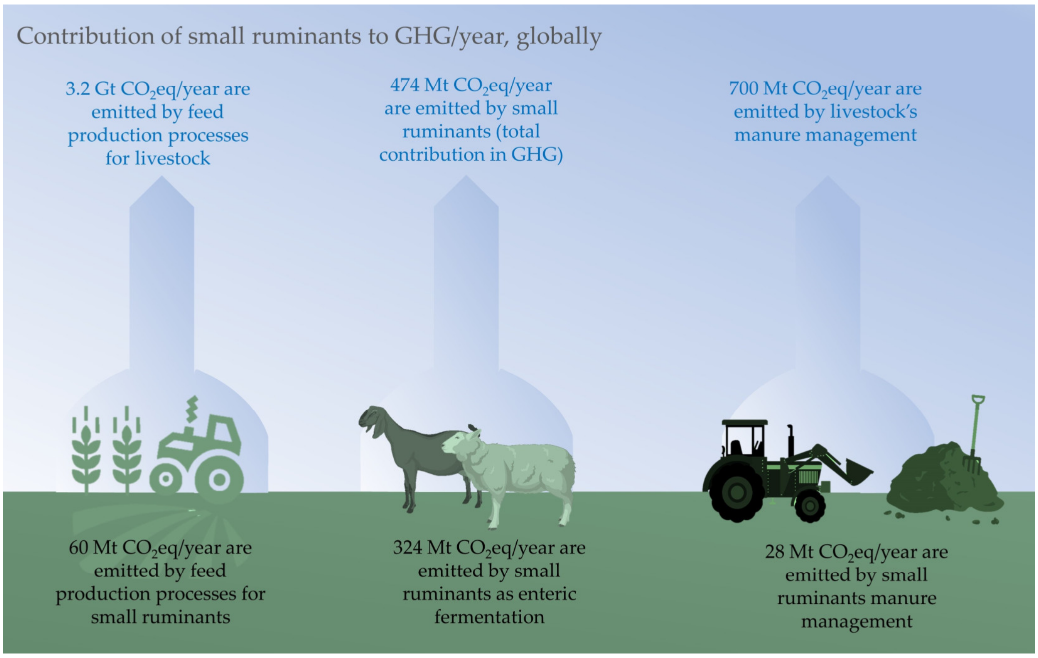

Figure 1. Contribution of small ruminants to GHG/year, globally. Blue color letters: general data about livestock's GHG contribution such as feed production, including rice products and manure management, and excluding manure application on feed crops or pasture, and total contribution of small ruminant sector, were obtained by Gerber et al. [6]. Black color letters: data about small ruminants' GHG emission related to feed production, manure management and enteric fermentation were accessed by GLEAMv3.0 on 14/02/2023 using the AR6 equation (CH_4 = 27, N_2O = 273) [16]).

2.1. Sources of Methane (CH_4) Emissions

Methane is the most important greenhouse gas generated from the animal sector [17]. In ruminants, methane (CH_4) is mainly produced by enteric fermentation and manure storage [18]. More than 55 percent of emissions from small ruminant meat and milk production originate from enteric fermentation and the vast majority is formed in the rumen by methanogenic microbes. Therefore, any mitigation strategy that reduces methanogen populations and consequently methane emissions should not be limited to it but also include an alternative pathway for H_2 neutralization since its accumulation can impair rumen function [19]. In ruminants, methane emissions represent a loss of about 2 to 15% of dietary gross energy [20]. Sheep and goats produce 10 to 16 kg CH_4/year and cattle 60 to 160 kg/year, depending on their size and dry matter intake (DMI) [21] and, especially in Greece, CH_4 represents the main GHG from agriculture, with a contribution ranging from 48% to 58% [22].

2.2. Sources of Nitrous oxide (N_2O) Emissions

Slightly more than 35 percent of N_2O emissions derive from feed production, whereas manure emissions are lower because manure is mainly deposited onto pasture [6]. Crop activities in small ruminants' farms involve forage and grain production for livestock feeding but also crop production for sale. Direct N_2O emissions from manure storage are lower compared with CH_4 emissions. Direct N_2O emissions occur from when manure is treated aerobically; at that time, organic N is converted to NO_3- and NO_2- through nitrification and then manure is treated aerobically where N_2O and NO are produced through denitrification [23]. The N_2O emissions from manure management account for 20%, 25%, and 34% of total emissions for the extensive, semi-intensive, and intensive dairy goat farming systems, respectively [13].

2.3. Sources of Carbon Dioxide (CO_2) Emissions

Carbon dioxide emissions are mainly generated from anaerobic degradation of manure, producing biogas [24] and combustion of fuel [25]. Carbon dioxide is linked to the energy combustion of mixed crop and livestock farms. This energy use is related to fuel use (mainly diesel) and electricity [26], which is attributed to the milking machinery, the transportation, the ventilation equipment used in the animal houses, and the whole crop production use if the feed is produced on site. The emissions from this combustion can be accounted for by estimating the requirements for energy use, fuel, electricity, and type of machinery used for every farm operation, multiplied by the appropriate emission factors.

3. Sustainable Strategies for Mitigation of GHG Emissions

3.1. Feed Related Strategies

Methane represents a significant loss of dietary energy; thus, the aim is to reduce its production favoring both environment and feed conservation rate. Therefore, the key role on the mitigation practices for small ruminants is the manipulation of the methanogenesis route. Although there are several options for reducing methane, it has to be balanced so that an economically sustainable way for producers, together with the ability to improve the production efficiency, are supported simultaneously.

3.1.1. Forage Quality, Growth Stage, and Legumes Grazing

By improving pasture quality, the animal productivity may be enhanced and lower CH_4 will be emitted, with less dietary energy loss [27]. A mitigation option is the harvesting of forages at an earlier growth stage, in order to increase the soluble carbohydrates and decrease the lignification of cell walls (less NDF) [28]. This also would increase its digestibility, leading to a reduction in GHG emissions. A methane reduction is reported with the replacement of fibrous forage with unlignified immature grasses and early cut forage at a level of 15%, while for processed forages, the reduction was 21%, while for grass forage and good quality silage the reduction was 28% and 20%, respectively [29]. The overall objective is to combine the maximum yield of dry matter per hectare with the highest digestibility. For example, by shifting from higher cell wall content (C4) to lower (C3) grasses or even grazing on less mature pastures, mitigation of CH_4 production can be achieved [27]. Archimède et al. [30] recommended the use of C3 legumes in warm climates as a mitigation option, as animals fed warm climate legumes produced 20% less CH_4 than animals fed C4 grasses. Consumption of several levels of legumes by ruminants results in lower CH_4 yield than that associated with the consumption of grasses [27], due to the tannins content of some legumes [31]. In sheep fed diets with legumes such as white clover, *Lotus pedunculatus*, the outcome was 16% lower CH_4 production compared to sheep fed ryegrass [32]. At the same time, ryegrass cut at 21 d revealed ameliorated nutrient intake than that cut at 35 d, as well as increased microbial crude protein formation with silage feeding than with hay fed lambs [33]. Moreover, as reported by Gonzalez-Ronquillo et al. [33], the ensiling of ryegrass at 21 d had no negative effects in the nutrient intake, N balance, and sustainability of locally produced feed which could be an overall aim. Nevertheless, there are important benefits of legumes such as the replacement of mineral N fertiliser [34]. Further, the supplementation of 300 g/kg DM of rapeseed forage harvested at pod stage, presented assuring results as functioning as an alternative protein source for alfalfa hay, without affecting nutrient intake and digestibility [35]. Overall, the inclusion of less lignified forages into ruminants' diets appears to be an efficient strategy to increase organic matter digestibility and feed efficiency, therefore reducing the overall carbon footprint of meat and milk production while the optimum rumen conditions are preserved. However, further holistic studies should evaluate if the collection of forages at an earlier growth stage could negatively affect other socio-economic balances such as feed-food or inter-species feed competition.

3.1.2. Elevated Proportion of Concentrate Feed in Diets

The inclusion of concentrate feed at elevated rates of 35% to 40% of DMI in ruminants' diets may conceivably decrease the enteric CH_4, although it unambiguously depends on other factors such as the type of grain, etc. [19]. By including grain, the starch is raised while the NDF (Neutral Detergent Fiber) intake is lessened, a fact that subsequently reduces rumen pH and advances propionate over acetate production in the rumen [36]. Lovett et al. [37] indicated that the emissions of CH_4, N_2O, and CO_2 were reduced by 9.5%, 16%, and 5%, respectively, by increasing the feeding of concentrates in dairy cows. The inclusion of concentrate feeds will enhance animal productivity and a shrink in GHG emissions intensity will occur, but the absolute GHG emissions may not always decrease as a result of intense feed production [7]. Additionally, special attention should be paid to forage to concentrate ratio since the overload of rapidly fermentable carbohydrate reaching the rumen can impair its degradative potential and therefore animal performance.

3.1.3. Inclusion of Feed Supplements in Diets Manipulating Rumen Methanogenesis

Dietary Lpids

Dietary lipids' supplementation reduces CH_4 emissions [38] by interfering in rumen function. The effectiveness depends on the influence on animals' productivity and the cost of oil products. Researchers in Australia observed a 12% CH_4 reduction in dairy cattle [39] and a 42% CH_4 reduction in dairy cows [40] following the inclusion of cottonseed meal. For adding 1% lipids (limited to 6% supplementation level), the decrease of CH_4 was 3.5–5.4%, as measured in cattle and sheep [27,41,42]. Specifically, Grainger and Beauchemin [43] demonstrated that addition 10 g/kg of dietary fat in the sheep diet would decrease CH_4 emissions for meat production by 2.6 g/kg. Dietary lipids can be found in a plethora of feeds such as coconut oil and whole crushed oil seeds (rapeseed, sunflower seed, etc.) [44]. Moreover, Vargas et al. [45] added 6% of olive and linseed oil in rumen' diets and managed to reduce methane production by 21 to 28%. In recent studies, supplementing long chain fatty acids in the goat diet decreased methanogens population on both liquid and solid fraction in the rumen [46,47] unveiling promising scenarios for methane suppression. On the contrary, Cosgrove et al. [48] reported no mitigation result of lipid supplementation (in 0, 1.2, 2.5, 3.8, and 5%) to the sheep diet. The quantity of inclusion for avoiding negative effects in ruminants was kept between 4% and 8% of DMI [49]. However, it has been stated that it is the fatty acid profile of the fat source, rather than the fat level per se, that impairs rumen methanogenesis [50]. In this light, a plethora of scientific questions remain open such as, is it the absolute number of methanogens that correlated with methane formation or is it the microbiome structure [51]. Additionally, it must be highlighted if specific fatty acids affect specific rumen "residents" per se or if the disruption of their biofilm is compromising their structure or their metabolism. Understanding the regulatory mechanisms of specific fatty acids in rumen methane formation will shape the key manipulation strategy for ruminants GHG mitigation. On the other hand, it has been observed that fat mode of action in the rumen microbiome is not methanogenic-specific; thus, other microorganisms involved in feed degradation and volatile fatty acid production could be harmed as well. The deeper exploring of the inhibitory specificity of certain fatty acids against methanogenic species or the synergetic action of fatty acids and other feed additives and bioactive compounds aiming to target manipulate rumen populations can facilitate the on-farm scale implementation of such strategies.

Electron Receptors

In rumen, archaea produce CH_4 during fermentation, mainly by using H_2 and CO_2 as substances [49]. Nitrates are used as electron acceptors, replacing CO_2, so that NH_3 is produced instead of CH_4 [36], which also negatively affect soil and water. Further, nitrates have been shown to reduce CH_4 production in sheep [52], with the actual level of reduction being 23% in KNO_3-supplemented sheep [53], 16% with nitrate supplementation in dairy cows [54], and 17% after supplementing forage-based diets in finishing beef cattle [55]. However, nitrate must be supplemented with caution as it can be toxic above certain doses [21]. Other electron receptors such as fumaric or myristic acid have been tested and reviewed, showing reductions of CH_4 [36]. In cattle, inclusion of 2% fumaric acid in silage reduced CH_4 by 23% [56]. Wood et al. [57] provided 100 g kg^{-1} fumaric acid in a free form to lambs and reported a 62% reduction in CH_4 output while in an encapsulated form found a 76% reduction. Moreover, in sheep, myristic acid (50 mg kg^{-1} DM) reduced CH_4 by 22% when fed in a forage-based diet and 58% in a concentrate-based diet [58]. However, due to the high doses required, dicarboxylic acids are too expensive to be used widely [59].

Microorganisms

This category contains mainly suggestions based on the activity of yeast and some bacteria, widely known as acetogens. Previous research conducted by McGinn et al. [60] using two strains of yeast (Levucell SC and Procreatin-7) in beef cattle demonstrated no effects on CH_4 production. Conversely, yeast products, based on *Saccharomyces cerevisiae*, can decrease CH_4 by promoting rumen fermentation [61]. Similarly, Grainger and Beauchemin [44] reduced CH_4 emissions by 7% but negative effects on rumen pH followed. Moreover, another effective way could be the utilization of bacteriophages [62], based on their ability to specifically target methanogenic archaea and surpass host's cells, which has already shown promising results for methane mitigation [63]. However, more emphasis on the metagenomics part of the phages' identification is needed.

Antibodies and Vaccines

Due to the rising concern over the use of antibiotics, new areas of interest have been researched. Subharat et al. [64] examined the prospect of immunization and production of antibodies over methanogens. A vaccine targeting the cell surface or membrane proteins of methanogens may establish vaccination as an effective CH_4 mitigation practice [36,65], by diminishing the methanogen population or its activity in rumen. In the same context, Wright et al. [66] managed to decrease CH_4 production in Australian sheep using a vaccine over specific methanogens, but did not have the expected results with different microbial species or rearing conditions [36]. Nevertheless, this approach is based on the possible cost neutrality of the action but needs further research regarding the complexity of the target species.

Enzymes

In a meta-analysis on the effects of exogenous fibrolytic enzymes in ruminant diets, Tirado-González et al. [67] reported that enzymes may improve the productive performance of dairy cows and beef cattle, but the response depends upon the proper ratio of cellulases to xylanases according to the diet's composition. The addition of cellulases and hemicellulases in ruminants' diets improved fiber digestion and productivity [27,68] and, thus, reduced in vivo CH_4 production by 28% and 9%, respectively [27].

Plant Bioactive Compounds

This category includes a variety of plant secondary compounds that are used as feed supplements, such as tannins, saponins, essential oils, plant extracts and their ingredients, that have exert anti-protozoal effects and decrease the enteric emissions [69]. Tannins have a great variety of type, concentration, and protein-binding capacity as well as technique accounting for the plants' concentration [70], so the effects differ among studies. For instance, the dietary supplementation of chestnut tannins, examined in vitro, portrayed beneficial results for methane and ammonia emissions without affecting acetate production and thus inducing a promising solution for reducing them [71]. Moreover, low CH_4 yield has been shown on pastures rich in condensed tannins [32]. Furthermore, Carulla et al. [72]

managed to decrease CH_4 emission by 13% with a partial replacement of tannins from *Acacia mearnsii* included in the sheep diet. Similarly, Tiemann et al. [73] indicated that 25 g/kg DM of tannins of *Calliandra calothyrsus* and *Flemingia macrophylla* reduced CH_4 yield by 13%. Further, for Angora goats fed with *Lespedeza cuneata* containing condensed tannins, CH_4 production was reduced compared to goats fed a combination of *Digitaria ischaemum* and *Festuca arundinacea* [74]. Likewise, the same anti-protozoal properties can be ascertained for plant saponins [27], flaunting some vital potential, but still more and extended studies are required before they could be recommended for use [21]. The same potential was presented by in vitro research of green tea ethanolic extracts to lessen methanogenic processes by using four doses (250, 500, 750, and 1000 µg/mL) which concluded in supplementing the lowest dose as better adapted [75]. However, considering methane mitigation through essential oils, Cobellis et al. [76] pointed out by summarizing the effect of essential oils as rumen modifiers that the in vivo reduction of methane yield seems to be fictitious since there is ample evidence that indicates an overall degradative suppression in the rumen due to their action.

Although essential oils and other bioactive compound derivatives of plant materials have been extensively investigated as rumen methane mitigation agents, their on-farm scale implementation, accompanied by crucial limitations such as the amount that the livestock sector needed, the financial sustainability of its inclusion in animal diets, the food-feed and nutraceutical industry competition, etc.

Chemical Inhibitors

Halogenated analogues, such as bromochloromethane (BCM), 2-bromo-ethane sulphonate (BES), and chloroform are potent inhibitors of CH_4 formation in ruminants [49]; thus, considerable reduction can be achieved by utilizing them [21,77]. Although some compounds such as BCM are banned and therefore cannot be recommended, other compounds with a similar mode of action could be acquired [21]. Such compounds can be found in macroalgae, such as *Asparagopsis taxiformis*, which is acknowledged to potentially reduce enteric CH_4 production, by inhibiting cobamide-dependent methanogenesis [78]. The same researchers reported 50 to 80% CH_4 reduction over a 72-day feeding period by adding 3% of *Asparagopsis taxiformis* to the sheep diet, in comparison with lower inclusion levels. Roque et al. [79] mentioned a 95% reduction in CH_4 by adding 5% of feed organic matter of the same macroalgae species to the diet of dairy cows. Similar results were shown by Kinley et al. [80] when steers received 0.10% and 0.20% of *Asparagopsis taxiformis* and CH_4 decreased up to 40% and 98%, respectively. However, Patra [69] described the risk of toxicity, even up to death, after a long period of consumption. Recent research has identified alternative approaches capable of inhibiting methanogenesis, such as 3-nitrooxypropanol (3NP) [81], which achieved 24% reduction in CH_4 emissions in sheep [77] and up to 70% in cattle [82,83], while nontoxic effects were observed [21,84].

Amino Acid

Furthermore, more practices should be adapted in order to decrease the environmental burden and maximize the exploitation of nutrients. Amongst these, amino acids operate a fundamental role not only in fulfilling the protein needs but also in the bioavailability of nutrients, such as nitrogen efficiency [85], thus reducing the cost and increasing the environmental effectiveness [86]. Furthermore, amino acids are vastly involved in animals' metabolic processes, improving growth and reproductive performance plus strengthening the immune system [87]. In spite of this, the combination of amino acids with trace elements, under the format of chelated amino acid, could also be a favorable practice not only for the N use efficiency but to the total feed efficiency and performance burden [88]. A summary of the practices mentioned below is presented in Table 1.

Table 1. Feed-related strategies applied for the mitigation of GHG emissions.

Feed-Related Strategies	Nutritional Practice	Impact on GHGs Emissions	Animals	Reference
Replacing fibrous forage	Unlignified immature grasses and early cut forage	↓ 15% CH_4 (g/kg DMI)	Ruminants—modelling approach	[29]
	Processed forage	↓ 21% CH_4 (g/kg DMI)		
	Use of grass forage	↓ 28% CH_4 (g/kg DMI)		
	Good quality silage	↓ 20% CH_4 (g/kg DMI)		
Replacing C4 grasses	Use of C3 legumes in warm climates	↓ 20% CH_4 (L/kg OM)	Ruminants—meta-analysis	[30]
Replacing ryegrass	Legumes white clover, *Lotus pedundulatus* (condensed tannins)	↓ 16% CH_4 (g/kg DMI)	Sheep—in vivo	[32]
	Ryegrass cut at 21 d instead of 35 d	↑ nutrient intake, N balance	Sheep—in vitro	[33]
	300 g/kg DM rapeseed forage harvested at pod stage	– nutrient intake and digestibility	Sheep—in vitro	[35]
Inclusion of concentrate feed	Elevated levels of concentrate feed (35–40%)	↓ 9.5% CH_4 ↓ 16% N_2O ↓ 5% CO_2	Ruminants —modelling approach	[37]
Inclusion of dietary lipids	Cottonseed meal	↓ 12% CH_4 (g/cow/day)	Dairy cattle —in vivo	[38]
	Cottonseed meal	↓ 42% CH_4 in dairy cows	Dairy cows—in vivo	[40]
	10 g/kg dietary fat	↓ CH_4 for meat by 2.6 g/kg DMI	Sheep—meta-analysis	[43]
	6% oil and linseed oil	↓ 21–28% CH_4 (mL/d)	Sheep—in vitro	[45]
	Lipid supplementation in 0, 1.2, 2.5, 3.8, and 5% in sheep diet	– alteration (g/kg DMI)	Sheep—in vivo	[48]
Inclusion of electron receptors	Nitrate KNO_3 in sheep	↓ 23% CH_4 (L/kg DMI)	Sheep—in vivo	[53]
	Nitrate in dairy cows	↓ 16% CH_4 (g/kg DMI)	Dairy cows—in vivo	[54]
	Nitrates in forage-based diets in beef cattle	↓ 17% CH4 (g/kg DMI)	Beef cattle—in vivo	[55]
	2% fumaric in cattle silage	↓ 23% CH_4 (L/d)	Cattle—in vivo	[56]
	100 g/kg fumaric acid in free form	↓ 62% CH_4 (L/d)	Lambs—in vivo	[57]
	100 g/kg fumaric acid in encapsulated form	↓ 76% CH_4 (L/d)	Lambs—in vivo	
	50 mg/kg DM myristic acid to concentrate based diet	↓ 58% CH_4	Sheep—in vivo	[58]
	50 mg/kg DM myristic acid to forage-based diet	↓ 22% CH4		
Inclusion of microorganisms	2 strains of yeast (Levucell SC and Procreatin-7)	– CH_4 (g/kg of DMI)	Beef cattle—in vivo	[60]
Enzymes	Addition of cellulases and hemicellulases in ruminants	↓ 28% CH_4 and 9% respectively (g/g DMI)	Dairy cows—in vitro	[28]
Plant bioactive compounds	Tannins from *Acacia mearnsii*	↓ 13% CH_4 (kJ/MJ energy intake)	Sheep—in vivo	[72]
	25 g/kg DM of *Calliandra calothyrsus* and *Flemingia macrophylla*	↓ 13% CH_4 (kJ/MJ gross energy intake)	Lambs—in vivo	[73]
Chemical inhibitors	3% of *Asparagopsis taxiformis* in sheep for 72-day feeding period	↓ 50–80% CH_4 (g/kg DMI)	Sheep—in vivo	[78]
	5% feed organic matter of *Asparagopsis taxiformis*	↓ 95% CH_4 (ml/g OM)	Dairy cattle—in vitro	[79]
	0.10–0.20% of *Asparagopsis taxiformis*	↓ 40–98% CH_4 (g/kg DMI)	Steers—in vivo	[80]

↓ = decrease, ↑ = increase, – = no effect, DMI = dry matter intake, OM = organic matter.

3.2. Energy-Related Strategies

Energy management is an important factor for sustainable livestock production and mitigation strategies. Primarily, measures should be taken to improve the heating requirements of livestock buildings. Furthermore, using, selecting, and maintaining efficient lighting systems, exhaust fans or milking machines, and improving building insulation appear to be of paramount importance. In addition, an immediate reduction in GHG emissions can be achieved by replacing fossil fuels with renewable fuels such as wind, solar, biomass, energy crops, and energy from CH_4 produced from manure [89]. In addition, farm buildings should be heated, ventilated, cooled, and lit using renewable energy sources, such as roof-mounted solar panels [90]. In addition, LED technology is more reliable, energy efficient, longer lasting, and greener. Nonetheless, it is crucial to install and maintain a simple control sensor system, for example, temperature control sensors to preserve the appropriate temperature.

3.3. Manure-Related Strategies

Animal manure is generally classified into liquid, slurry, and solid. Its management can lessen the hazards for GHG emissions as well as environmental pollution and public health. Manure management includes collecting, storing, treating, transporting, and disposing of manure. An efficient system needs to keep manure and its hazardous constituents off the environment, and concurrently be profitable. Furthermore, by applying it properly on the field for fertilization and feed production, the reduced use of nitrogen fertilizer and subsequently nitrogen loss can be achieved.

3.3.1. Storage

For proper management, animal houses must allow the easy collection to prevent losses. The floor of the house should be covered from rain to prevent loss of nutrients due to evaporation, runoff, and leaching. Frequent removal from animal housing is required for the prevention of manure fermentation and GHG emissions, as a storage period extension can raise CH_4 emissions [21,83]. The area in which the manure is to be stored should be in compliance with the appropriate time limits so that there is proper time for digestion. Additionally, the duration of storage is highly dependent on the climatic conditions and, as a result, may vary depending on the conditions, from 3 months in drier countries including Greece to even 10 months in Finland [91].

Covering

Storage of liquids should be assembled in tanks that can be covered or opened, and sealed with specific water permeability indicators [21,92–94]. Covering liquid manure maintains aerobic conditions during storage that can help reduce N_2O and CH_4 emissions and regulate the odors from NH_3 emissions. Less CH_4 is produced by solid manure or when deposited on pasture or rangelands [23]. The average CH_4 emissions as reported by Chianese et al. [25] were 6.5, 5.4, and 2.3 kg per m^2 per year from covered, uncovered slurry, and manure in stacks, respectively. N_2O emissions from liquid manure are negligible during storage unless a surface crust is present, while a crust may create N_2O emissions while drying and aerobic conditions are developed [92,95]. The use of straw as a cover for dairy cattle slurry, instead of a solid cover may produce higher CH_4 and N_2O emissions [96]. Covering semipermeable manure may reduce NH_3, CH_4, and odor emissions, but possibly increase N_2O emissions [93,94].

Cooling

An applicable practice, not expensive yet simple and efficient, is the cooling of manure [97]. Nevertheless, the proper temperature conditions for the storage of liquid manure should be lower than 15 °C, as this has been reported to decrease the methane emissions [98]. In the same line, the combination of frequent emptying and slurry cooling can be used in cold or mild climates under conditions of significant temperature difference [99].

3.3.2. Process

There are various methods available for treating manure from simple to extremely complex. Firstly, the separation into liquids and solids. The addition of solid materials to the liquid manure is appropriate. Külling et al. [100] showed that farmyard manure and deep litter manure handling systems tend to produce greater N_2O emissions than slurry-based systems.

Anaerobic Digestion

The process of anaerobic digestion refers to the deprivation of microorganisms occurring under anaerobic conditions. The outcome is the generation of CH_4, CO_2, and other gases as by-products. The aftermath is energy production, mainly biogas in the first place. However, the biogas can produce electricity, and electricity is on the last level of the process, thus signifying a very promising approach for lessening the burden of the GHG emissions from manure and energy [101]. Therefore, biogas can replace and decrease farms' fuel combustion, implying it as one of the most promising practices. The production of biogas by materials such as biomass, manure, sewage, municipal waste, green waste, or plant material and energy crops [102–104] makes it a relatively simple practice that can be efficient at a large or small scale (village and household level) [105].

Composting

Composting is a natural exothermic process of aerobic decomposition, where microorganisms transform degradable organic matter into CO_2 and water [95,106], providing several advantages pertaining to manure handling, odor, pathogen control, organic matter equilibrium, additional farm income, etc. [21] as well as lower density. Composting can be organized in piles or ditches, either on a small or large scale whereas solid or liquid manure can be used. Aeration may reduce CH_4 but increase N_2O and NH_3 emissions [21,107,108] due to the probability of generating aerobic environment, but the benefits on lessened odor and CH_4 emissions, compared with anaerobically stored manure, make it a favorable option [21].

Acidification

Another modest recommendation is the use of acidic agents for NH_3 emissions [21,109]. For instance, 14 to 100% reduction in NH_3 emissions was reported by Ndegwa et al. [110], by applying sulfuric, hydrochloric, or phosphoric acids and 67 to 87% reductions in CH_4 by using sulfuric acid (pH of 5.5) [111]. However, the long-term impact of acidified manure applied on soil pH have not yet been reported [21].

Ventilation-Biofiltration

A ventilation system provides the opportunity to filtrate emissions from facilities or absorb them. Singh and Mallick [112] reported that the utilization of ventilation air methane is considered as the most effective strategy to reduce methane emissions but nonetheless a challenging one from the economical perspective. Additionally, some chemical compounds show promising results based on filtration of NH_3, NO_2, or even CO_2. For example, the stimulation of photocatalytic properties the using of TiO_2 by UV light, oxidates NH_3 and NOx [113,114] by using titanium dioxide (TiO_2) paint on the walls [115,116]. Another option is the use of oxides or hydroxides as well as carbonates or bicarbonates which are known to exert high CO_2 absorption and have therefore been examined as such [117].

3.3.3. Distribution and Deposition of Manure

Manure is a valuable source of available nutrients for crops, successfully replacing artificial fertilizer [21]. However, there are a plethora of factors such as the type of soil, moisture or the application technique affecting the level of emissions. Measures such as improved timing (e.g., avoiding application before a rain), fitting nutrient application to crop requirements [12,21], as well as avoiding spreading slurry on wet soils [118] can reduce emissions and additional cost for farmers. Another option is the dilution or reduction of degradable carbon by solid separation or pre-treatment of anaerobic degradation [96,119]. Useful also could be the control of the nitrogen amount available for nitrification and denitrification in soil [21].

A summary of the described applications is presented in Table 2.

Table 2. Sustainable strategies applied in manure for the mitigation of GHG emissions.

Manure Related Strategies	Practice	Impact on GHG Emissions	References
Storage of manure	Covering dairy cattle slurry with straw instead of solid cover	↓ CH_4 and N_2O	[96]
	Semipermeable covering	↓ NH_3, CH_4 and odour ↑ N_2O	[93,94]
	Cooling slurry below 15 °C	↓ CH_4	[98]
Process of manure	Anaerobic digestion	↓ emissions from manure and energy	[101]
Acidification	Sulfuric, hydrochloric or phosphoric acids	↓ 14–100% NH_3	[110]
	Sulfuric acid (pH = 5.5)	↓ 67–87% CH_4 (mg/kg/h)	[111]

↓ = decrease, ↑ = Increase

3.4. Other Strategies

3.4.1. Precision Feeding

Precision feeding is a technique that aims to harmonize nutrient requirements of the different animals with the nutrient supply. A sustainable technique for nutrition is precision feeding in order to maintain a healthy rumen and to maximize feed efficiency as to decrease CH_4 production [21]. Some promising results have already been shown, presented as enhanced ewes' milk production efficiency by 50%, as well as 42% lower environmental impact measured as kg of FPCM milk (fat protein corrected milk) in a comparative study of innovative farms that used precision feeding versus conventional ones [120]. However, since it needs specific feed, equipment and management practices, it is not easily adapted by extensive farmers because there is a lack of data on the nutrient requirements of the animal breeds and on the quality of feed [21].

3.4.2. Genetics and Selection

The concept of this category is the selection of breeds that emit low levels of GHG; so, to attain this, it is of foremost importance to further understand the mechanisms underlying the correlation between host genetics and the rumen microbial consistency to obtain optimal production with low environmental impact [121,122]. Therefore, a suggestion considerably effective yet simple and reliable, is the handling of animals with low emissions through genetics selection, as the trait for low emissions is heritable [123,124]. Moreover, the host's genome can affect the CH_4 generation by triggering the growth of certain microbes that regulate the amount of H_2 [125]. This premise is based on the perception that host–microbiome interaction is substantially orchestrated by host's genes; thus, the methanogens inhabitation and the methane formation could be manipulated through animal selection.

4. Circular Bio-Economy Sustainable Strategies in Ruminant Nutrition

4.1. WASTE Material: Food Waste as an Alternative Feed Source

Every year on a global scale about 32% of the food produced gets lost or wasted [126]. About 800 million people could cover their needs for food more than four times with this portion of food [127]. One third of the total food produced every year are lost or wasted, which accounts for 1.3 billion tons of food that was destined for human consumption. In the food supply chain, food might be lost or wasted in every stage. In the early stages of the food chain, during production, post-harvest and processing the food loss occurs [127–129], while in the stages of retail and consumption the food waste occurs [128–130].

Inadequate handling of food waste is responsible for negative environmental impacts and many methods are used for disposal. Some widely used methods are anaerobic digestion, composting or discarding in landfills. An alternative option of recycling food waste might be its use as feedstuffs [131]. Food waste is a valuable source of energy and nutrients and can be used in animal diets. The utilization of food waste is an economic and sustainable method that also reduces the cost of animal feeding [132]. However, there are many obstacles that makes difficult the reutilization of food waste as feedstuffs. The high content of moisture [132], the variability of nutrients [19] or the potential content of pathogenic microorganisms are some of them. Moreover, factors such as the source of collection [133], the period of the year [134] and others [135–138] could determine the composition of food waste.

The mixing of food waste with other feedstuffs is a practical method to overcome these nutritional obstacles and create a balanced diet for animals [139]. Food waste can be fed in different forms, such as wet, dried or ensiled. In the angle of safety, many safety concerns emerge for the direct utilization of food waste in animal diets. This is the reason that many prohibitions are enforced in the European Union about its use in animal diets [140] and many regulations are applied in the United States [141], Japan, South Korea and Taiwan [142].

4.2. Use of Agro-Industrial By-Products in the Diets

Agro-industrial by-products are considered as a valuable and cheap feed ingredient for animal nutrition. A sustainable utilization of these products is supported within the food chain, developing a circular economy strategy. Meanwhile, in the last decades consumers seem to have moved towards natural and clean animal products from farms which follow a sustainable approach in order to be safe and healthy [143]. The use of agro-industrial by-products in ruminant diets could support their growth and productivity, resulting in edible food for human consumption. Many assets could emerge, such as a reduced feed cost for farmers, the production of value-added products or an improved health profile for animals [144].

The different types of agro-industrial by-products are obtained during processing methods, such as the production of oil, sugar, products derived from fruits or vegetables, roots or tubes [145]. Production of wine and oil are corresponded for grape and olive pomace, fruit by-products (apple, citrus) are derived from fruits, jelly or jam industries and vegetable by-products from the processing of tomatoes, potatoes or carrots [146]. All of them can be used as raw materials or after processing with several methods, for example drying or more advanced techniques in order to pick specific compounds. However, there are some limitations concerning their use, with the most important of them the large compositional variability depending on the processing method used, as their availability is strictly affected by the season of the year and the area, while undesirable contaminants with or inorganic origin are present [147,148]. Preservation treatments are important for product stabilization, seasonal availability and for the increasing of products' shelf-life, especially for those rich in moisture and lipids [149,150].

4.2.1. Apple By-Products

The process of apple fruit generates large quantities of solid and liquid by-products. As far as the solid part is concerned, it consists mainly of skin, pulp and seeds that are generated from the production of apple juice, jam and sweets and is known as apple pomace. The disposal of apple waste is connected with the release of greenhouse gases, because as a high biodegradable material it is disposed of in landfills, incinerated or sent for composting [151].

Using apple pomace in animal diets could help to reduce the environmental issues of disposal. Rich in fermentable carbohydrate, pectin, crude fiber and minerals, it is a valuable industrial by-product for ruminant diets [152]. Steyn et al. [153] replaced ground maize with dried apple pomace in the diets of Jersey cows in order to study its effect on milk yield, with four inclusion levels (0, 25, 50, 75%). They found no differences concerning the composition of the protein and fat of the milk. A mix of ensiled apple and tomato pomace in a ratio of 50:50 was used by Abdollahzadeh et al. [154] in order to evaluate the performance of Holstein cows. According to their results, this mix could replace 30% of cows' diet with a small increase in milk production, and with no other adverse effect.

4.2.2. Citrus By-Products

The remaining residues of citrus fruits from juice extraction are considered as the citrus by-products [155]. It consists mainly of peels at about 60–65%, 30–35% is the pulp and 0–10% from seeds. Citrus pulp is an extraordinary source of energy for ruminants. The utilization in animal diets could limit management problems concerning the disposal of citrus residues. The dried citrus pulp is also rich in fiber and calcium and can be a valuable and cheap feedstuff. Fibers from citrus contains associated bioactive compounds (flavonoids) and this is a remarkable trait compared to the usual dietary fibers.

In the diet of dairy cows a replacement of corn grain (in 0, 15, 30%) with pelleted citrus pulp was studied by Santo et al. [156]. They did not observe any negative effect on the composition and quantity of the milk produced. Moreover, effects in many parameters were studied after the inclusion of citrus pulp and the replacement of cereals in sheep diets. Accordingly, meat oxidative could improve with an inclusion of 24–35% [157,158] of the protein content [159] and an increased concentration of meat PUFAs [160]. Different levels of citrus pulp (10–45%) were evaluated [161,162] and no significant effects were found in lamb growth performance parameters, feed intake and carcass traits.

4.2.3. Grape By-Products

Grape by-products are derived during the destemming, pressing and extracting process of grapes. Annually, large portions of grape waste are produced, posing management concerns [163]. Waste from grape processing are mainly stems and grape pomace such as grape skins, stems and seeds that compose the solid part [164]. From the total amount of waste, grape pomace accounts for 62%, wine lees accounts for 14% and stems 12% [165].

In a study carried out by Moate et al. [166], a reduction of methane emissions of about 20% was observed when dairy cows consumed about 5 kg of grape pomace per day. Moreover, no negative effects were found in milk quality traits and plasma biochemical parameters with the exception of urea in cows fed 3 kg/day grape pomace [167]. In fattening lambs, the inclusion of 10% in their diets did not affect their growth performance [168]. Furthermore, as far as the meat fatty acid concentration is concerned, a significant increase in linolenic acid and an improvement in oxidative stability of the meat was observed [169].

4.2.4. Olive By-Products

The extraction of olive oil generates large quantities of olive by-products that can lead to the degradation of the environment (pulp, skin, olive grains) [170]. An approximate amount of 800 g olive cake are produced by 1 kg olives [171]. The use of olive by-products in livestock diets would alleviate the environmental impacts caused and eliminate the feeding cost of animals [172]. Due to its high fiber content, olive cake could be used in ruminant diets. The composition content of it depends on the cultivation technique, the method of oil extraction, factors that affect the nutritional value and the preservation techniques that were followed [173].

Many studies were carried out in order to investigate any possible effects on the growth performance, after the inclusion of olive cake in ruminant diets, with neutral or positive results. An addition of 15% olive cake had no significant negative results in the daily weight gain, final body weight and dressing percentage of lambs [174]. Farmers could reduce lambs' feeding cost by 75%, with the use of olive-cake based feed blocks, with no negative effect on their performance [174]. Moreover, Chiofalo et al. [175] used olive cake to substitute cereals in beef cattle diets. In that study, after the inclusion of 7 and 15%

olive cake an increase in the body weight, average daily weight gain and carcass traits was found.

4.2.5. Tomato By-Products

The quantity of tomato grown every year on a global scale is estimated at 180 million tons [176]. The production of tomato juice and puree related with the generation of several wastes, mainly peels and seeds. About 4.5% of the fresh tomato weight accounts as residues, 3.5% comes from peels and 1.5% comes from seeds. Tomato pomace is a by-product of the canning industry depending on the following procedure and the source of raw tomatoes. The high moisture content is a limiting factor that decreases the storage life of this by-product. It can be used in animal diets fresh, dried or ensiled as an alternative and economic feed.

Tomato by-products could be used in ruminant diets as a valuable and cheap ingredient, representing a rich source of energy and nutrients. The addition of tomato by-product at a level of 40% could improve the quantity and the quality of milk but did not affect physiological characteristics of goats [177]. The supplementation of fattening ruminants diets with tomato pomace at the level of 180 g/kg did not affect negatively rumen fermentation [178,179].

A summary of the aforementioned strategies is presented in Table 3.

Table 3. Circular bio-economy sustainable strategies applied in ruminants' nutrition.

Strategies	Practice	Effects in the Sustainability	Reference
Precision feeding	Innovative vs. conventional farming systems	↑ 50% in milk production of ewes and ↓ 42% CF (kg CO_2eq/kg FPCM)	[120]
Amino acids and trace elements		↑ feed and N efficiency	[88]
Waste valorization	Food waste	Recycling food waste Reduce cost of feeding	[131] [132]
	Agro-industrial By-Products		
Replacement of ground maize	0, 25, 50, 75% dried apple pomace in diets of dairy cows	– protein and fat in milk	[153]
	50:50 ensiled apple and tomato pomace	↑ milk production – adverse effect with inclusion of 30%	[154]
Replacement of corn grain in dairy cows	0, 15, 30% of pelleted citrus pulp in dairy cows' diet	– composition and quality of milk	[156]
Replacement of cereals	Different levels of citrus pulp in sheep diet	↑ 24–35% oxidative stability ↑ protein content ↑ meat PUFAs	[157,158] [159] [160]
	Different levels 10–45% in lambs	– growth performance parameters, feed intake, carcass traits	[161,162]
	5 kg of grape pomace/day in dairy cows	↓ 20% CH_4	[166]
	10, 15, 20% grape pomace in lamb diet	– performance on level of 10%	[167]
	15% olive cake	– daily weight gain, final body weight, dressing percentage of lambs	[174]
	7 and 15% olive cake	↑ body weight, average daily weight gain, carcass traits of beef cattle	[175]
	40% tomato by-product in goat diet	↑ milk composition and production – physiological characteristics of goats	[177]
	60, 120, 180 g/kg tomato pomace in fattening ruminants	– rumen fermentation	[179]

↓ = decrease, ↑ = increase, – = no effect

5. Conclusions

Conclusively, there is a plethora of actions for maintaining sustainable and environmentally friendly small ruminant production. As has been described, the nutritional strategies, mainly through the utilization of novel feed ingredients, additives and practices over those previously well established (e.g., insects, agro waste or by-products) have been regarded as potentially promising options. Moreover, the nutrition also affects manure content and thus the emissions generated. Therefore, options for the manure as well as the energy, needed for the farm operations, underline another way of sustainable production. The composition of the proportions and additives affect the form and amount of N manure. The future is promising if available strategies are applied in time.

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