Indian J Anim Health (2022), 61(2)- Special Issue: 33-40
DOI: https://doi.org/10.36062/ijah.2022.spl.03322

Invited Review Article

Sustainable mitigation of greenhouse gas emissions in small-scale ruminant production system

Y. A. Soltan[1] and A. K. Patra[2*]

[1]Animal and Fish Production Department, Faculty of Agriculture, Alexandria University, Alexandria, Egypt; [2]Department of Animal Nutrition, West Bengal University of Animal and Fishery Sciences, Department of Animal Nutrition, Kolkata- 700 037, West Bengal, India

Abstract

The smallholder livestock sector is a key player to improve developing countries' food security under progressive climate changes. Thus, there is an urgent need to develop practical feeding livestock systems that can make smallholder livestock production farming systems more sustainable, productive, efficient, and environmentally friendly. The current review provides insights into the major strategies for maximizing smallholder livestock production using readily available options for mitigating greenhouse gas emissions employing feeding system improvements and production systems. The review also focuses on dietary management which is directly associated with the modulation of the ruminal fermentation pattern and types of the end animal products. These include enhancing the forage quality, changing the proportion of the diet, and adding dietary natural low-cost feed additives. The improved dietary management should be based on a combination of factors, including production type (milk or meat), herd management, genetics and breeding, animal health, and manure management. Recently, there are growing demands from policy and decision-makers to assess the adaptive and mitigation options of smart agriculture systems all over the world. However, the most important barriers for the small livestock holders sectors in the developing countries are the lack of awareness, insufficient capital and limited access to improved technologies. Establishing farmer agriculture schools in combination with specific policy interventions can be an innovative training extension program to deliver the needed information to these farmers, consequently enhancing the productive performance of their farming systems and enabling small farms to meaningfully operate and benefit from the small ruminant sectors.

Key words: Farmer awareness, Feed management, Greenhouse gasses, Herd health, Manure management

Highlights

- Small-scale ruminant production sectors are a main player to mitigate greenhouse gas (GHG) emissions.
- This review provides insights how dietary management directly linked to changes in the ruminal fermentation may reduce GHG emissions.
- The combination of dietary management along with herd management, genetics and breeding, animal health, and manure management should be considered.
- Enhancing the awareness of the livestock smallholders related to GHG mitigation strategies is required.

INTRODUCTION

Generally, the human population in developing countries is expected to be doubled by 2050 (FAO, 2013). Moreover, animal product demands are expected to increase due to population growth and animal product consumption, which may lead to the higher emission of greenhouse gases (GHG), impacting climate change and causing a threat to global food security (FAO, 2013). Therefore, all nations are required to mitigate GHG (IPPC, 2013); however, these aspects have created

*Corresponding Author, E mail: patra_amlan@yahoo.com

major challenges, particularly for smallholder livestock productions (the main contributors to the meat and milk supply) in the lower economic countries. This sector would face greater competition for capital, water, land, and energy to overcome the expected increased demand for animal-source foods (FAO, 2018). The concern about the emissions of methane from ruminants has increased in recent years due to the climatic change effects, and these gasses also represent a loss of feed energy which can be directed toward meat or milk production (Soltan and Patra, 2021). Methane (CH_4) is emitted from a variety of natural and anthropogenic sources. Anthropogenic emissions include oil and natural gas systems, landfills, wastewater treatment, agricultural and livestock activities, coal mining, stationary and mobile combustion, and certain industrial processes (Hoglund-Isaksson, 2012). It is estimated that the livestock sector accounts for 14.5% of total GHG emissions of anthropogenic origins (Gerber *et al*., 2013). Carbon dioxide (CO_2) and methane (CH_4) are the primary contributors to GHG (the United States Environmental Protection Agency, 2021). Methane is normally generated by ruminal methanogens using the fermentation end products (e.g., H_2, CO_2, and formic acid produced) (Patra *et al*., 2017), and represents 3 to 12% of the digestible feed energy loss (Patra and Lalhriatpuii, 2016). Around 110 countries have signed the Global Methane Pledge to reduce CH_4 emissions collectively by 30% from 2020 levels by 2030 (Beauchemin *et al*., 2022). Considering most of the ruminants are in the hands of small-scale livestock farmers, especially in the low economic countries of the world, this sector is a key player to mitigate GHG emissions and improve global food security (Rojas-Downing *et al*., 2017). Yet these farmers are ignorant to take climate change or the emission of GHG into account in their management systems. Therefore, any strategy to mitigate GHG production from ruminants would only be of practical interest if achievements of the animal efficiency of production could be obtained. Smallholder livestock is the most affected sector impacted by the recent global trends (e.g., Covid 19 pandemic and the Ukraine-Russia crisis), which consequently threatens global food security. Only practical and low-cost-effective applications for mitigating the emission of GHG from ruminants could make the smallholding sectors a sustainable productive and profitable activity.

Targeting climate and nutrition-oriented research concurrently could provide multidimensional benefits for society and our food chain systems while saving the planet. The current review gives insights into the main strategies for reducing GHG emissions by smallholder livestock production farmers through adopting different feeding systems.

Impacts of climate change on the smallholder livestock sectors

Climate changes negatively affect the smallholder livestock production systems, which play a vital role in the livelihoods of rural communities (Ates *et al*., 2018). Climate changes could also affect the quality of forages through modifications in lignification and the presence of plant secondary metabolites (e.g., phenols, alkaloids, and saponins), which could also impact both feed and food safety (Soltan *et al*., 2018). Moreover, climate change may result in other indirect adverse impacts, for example, greater emergence of livestock diseases, as higher temperatures and altered rainfall patterns can increase the distribution, prevalence, and transmission rate of animal pathogens (Baylis and Githeko, 2006).

For grazing systems, predicted increases in temperature and evaporation rates may increase the rainfall intensity, reduce pasture growth in summer, less grazing time, high water demands, and animal heat stress in summer (Kaufmann *et al*., 2021). However, there are potential benefits from climate change to pasture management including more pasture growth in spring and winter, reduced cold stress on animals in winter, and many changes in plant species and pasture composition can be accrued (Kaufmann *et al.*, 2021). The cut-and-carry system which depends on keeping the animals in enclosed pens can also be affected by climate change for smallholder farmers. As farmers follow this system due to limited pastures and restrictions of traditional grain crop production (Soltan *et al.*, 2012), climate changes may increase the cost of animal housing and the final animal products (Ates *et al.*, 2018).

Contribution of the small livestock sectors to the GHG emissions

The concern about the emissions of GHG from ruminants has increased in recent years and also this gas represents a loss of feed energy (Patra and Lalhriatpuii, 2016). Globally, GHG emissions from livestock increased over 50% during 1960 to 2010, mostly from developing countries (Caro *et al.*, 2014; Patra, 2014). Moreover, the recent global events including Covid 19 pandemic and the Ukraine-Russia crisis challenged the availability of imported feed resources and grains, drove prices to higher levels, and consequently threatened global food security. It seems that using the concentrate feeds would be difficult in regions where grain crops cannot be grown or are too expensive in countries such as North Africa (Beauchemin *et al.*, 2022). In this sense, smallholders are the sector most affected by these global trends, as they should be dependent on the local nitrogen-limited native grass pastures and agricultural wastes, which are characterized by high fiber contents, low energy, and digestibility, and consequently low feed efficiency. This substandard productivity may result in a very high cost in terms of GHG emissions per unit of milk or meat from small farms (FAO, 2018). Therefore, sustainable animal production under climate change cannot be achieved without practical significant strategies. The situation seems to be complicated; however, the following points are discussed in this review for some possible plans that may be adopted in the ruminant farming system.

Dietary management

Dietary strategies are commonly practiced approaches that can ensure increased animal productivity and reduce the GHG emission from ruminants. It can be divided into the following categories: enhancing the quality of forages, changing the proportion of the diet, and adding dietary local low-cost feed additives that directly alter the metabolic pathways towards less CH_4 production.

Forage quality: Pastures and forage crops are the main components of ruminant diets, utilizing about 70% of the agricultural areas globally (Beauchemin *et al.*, 2022), and thus they are the most available feed resources for smallholders compared to cereal grain crops (FAO, 2022). Improving forage quality, either through feeding forage with lower fiber and higher soluble carbohydrates can enhance feed efficiency and reduce CH_4 production (Adbdalla *et al.*, 2012). For example, CH_4 production with high soluble sorghum forage silage was lower compared with maize silage and low soluble carbohydrate sorghum forage silage (Zhang *et al.*, 2016). Reducing CH_4 produced by ruminants fed on forage-based diets will reduce the carbon footprint of livestock and improve the efficiency of animal production in developing and developed countries (Eugène *et al.*, 2021). Rodríguez *et al.* (2010) found that better synchronization of nitrogen and energy available for microbial utilization lowered CH_4 production. Improving forage quality also tends to improve voluntary feed intake and reduce the feed particle retention time in the rumen, allowing energetically more efficient post-ruminal digestion and lowering the proportion of dietary energy converted to CH_4 (Eckard *et al.*, 2010). Jayanegara *et al.* (2009) studied the relationships between chemical composition for 17 different feeds and CH_4 production and reported that, amongst the chemical constituents, neutral detergent fiber (NDF) had a high correlation with CH_4 concentration. The constituents of NDF also affect the CH_4

emission, because CH_4 produced per unit of cellulose digested is three times that of hemicellulose, and cellulose and hemicellulose are fermented at slower rates than non-structural carbohydrates, thus yielding more CH_4 per unit of substrate digested (McAllister *et al.*,1996). The forage quality can be enhanced in the following ways:

- Incorporating legume forages can reduce CH_4 yield more than grasses. The presence of specific plant secondary metabolites including condensed tannins (at low levels), high nitrogen, low fiber content, and a fast passage rate are the reasons behind the legumes effect (Soltan *et al.*, 2012; Eugène *et al.*, 2021). Moreover, the use of tannin-rich legumes shifts the nitrogen partition from urinary towards fecal N (Wang *et al.*, 2022), consequently, might reduce nitrous oxide (N_2O) emission (another potent GHG) emissions (Eugène *et al.*, 2021), and improve the manure quality to be used as soil fertilizers in the developing countries.
- Forage processing and preservation also influence CH_4 production, for instance, chopping or pelleting forages can lower the CH_4 emission relative to dry matter intake, as smaller particles require lesser degradation time in the rumen (Boadi *et al.*, 2004).
- Alternative forages that are adapted to harsh climatic conditions and can be grown on lands unsuitable for food grain production have immense potential for reducing GHG emissions as well as the feed deficits for livestock, and thus improving animal productivity contributing to food security, and diversifying the income of resource-poor farmers. For instance, salt-tolerant plants and shrub legumes (e.g., leucaena) are among these adapted forages that efficiently reduce CH_4 emissions without adverse effects on animal productivity (Soltan *et al.*, 2019).

Feed balancing: This has a positive effect of lowering emissions of GHG as a result of an effective supply of required nutrients to the ruminal microbes. This subsequently ensures that microbial anabolic processes minimize nutrient loss in the form of CH_4 and N_2O. In addition, balanced feeds will also improve health conditions as a result of corrections of nutrient deficiencies. The following are some factors that can affect ruminal methanogenesis:

- Carbohydrate composition: all carbohydrate fractions are responsible for CH_4 emission, of which the least contribution comes from starch. This occurs due to the maintenance of a propionate-dominating short-chain fatty acids profile. Propionate enhancement is the most efficient alternative H_2 sink way that can decrease the interspecies H_2 transfer between methanogens and protozoa and also increase energetic efficiency (Patra, 2016).
- Mixed carbohydrate sources: combining starch source grains that differ in their rate of ruminal degradation would provide a favorable grade of rumen available energy used by diverse rumen microbial communities to maximize microbial growth (Soltan *et al.*, 2021a). Replacing maize grains with low-cost, low ruminal degradable carbohydrate sources was found to enhance the animal growth rate and productivity, e.g., replacing maize grains with up to 667 g sugar beet pulp/kg diet resulted in enhancements in ruminal fermentation, nutrients digestibility, and growth rate of growing buffalo calves (Abo Zeid *et al.*, 2017)
- Ruminal microbial synthesis: the microbial protein accounts for 50 to 90% of the protein entering the duodenum (Eckard *et al.*, 2010). Thus, any enhancement of the absorbance of the microbial protein in the post-ruminal tract has to be directed into growth or milk production. The stable energy supply, for example, using slowly fermentable starch (e.g., corn) instead of rapidly fermentable starch (e.g., barley or wheat) to the ruminal microbes may play an important role in reducing CH_4 emission from ruminants through greater efficiency of energy

utilization and enhancing microbial protein synthesis. This can be obtained by decreasing the ruminal degradation rate of starch and enhancing its utilization in the post-ruminal tract by the host animal (Haque, 2018).

- Corn silage: generally, silage can contribute to reducing the ruminal emission of GHG compared to their fresh forms, because silage is already a fermented organic matter, and it may enhance the intake and passage rate to reduce the ruminal retention time, thus lowering ruminal fermentation and promoting post-ruminal digestion (Patra *et al.*, 2017). Lactic acid bacteria-based inoculants in silage may survive in the ruminal environment and positively enhance propionate production rather than acetate by buffering ruminal pH, consequently reducing the total CH_4 emission (Beauchemin *et al.*, 2022). Moreover, silage can be considered a stable forage source for ruminants, which can decrease the summer/autumn green forage gap typical of Mediterranean climates while making the small-scale livestock sectors a more productive and profitable activity (FAO, 2013).

Feed supplements: Optimizing animal productivity with feed supplements can be a very successful strategy for mitigating GHG emissions from the ruminant sectors. Free chemical and antibiotics modest price feed supplements are likely to be the most suitable way to enhance the animal productivity of the small livestock sectors. Supplements that enhance the feed digestion efficiency while reducing the GHG emitted by the unit of animal production are the best options to fit the objective of the climate-smart livestock feeding systems. These include exogenous enzymes, direct-feed microbial products (including live yeasts), probiotics, plant secondary metabolites, non-protein nitrogen sources, modified clays, and biochar (Patra, 2012; FAO, 2013; Soltan *et al.*, 2021b; Beauchemin *et al.*, 2022). The optimum dose, frequency, and mode of administration of these feed additives are not constant in the literature. Therefore, more applied research is required to establish their effects on high-forage diets.

Herd health management

For rural livestock smallholders, the loss of livestock assets means a redirection into chronic poverty and has long-term effects on their livelihoods. Maintaining healthy animals is always their major concern (FAO, 2013, 2018). High productive benefits may only be realized from healthy animals (FAO, 2013). In this issue, only healthy animals can produce higher milk and growth performance. Thus, expressing the emission of GHG per unit of animal product seems to be lower for healthy animals (FAO, 2022). Additionally, healthy animals have better adaptation mechanisms to the impacts of climate change, as high temperatures may result in increased pests including vector-borne diseases causing high economic losses (FAO, 2013). Animal health can affect animal fertility and mortality, which affects herd size to maintain production, thus affecting whole-farm GHG emissions. Moreover, variations in animal health due to diseases or parasite infections can be translated into metabolic changes such as reduced feed intake, lower nutrient digestibility, and increased requirements for maintenance energy that in turn increase the emission of GHG.

Animal health is affected by many factors of the production system, e.g., nutritional management, environmental stress, and preventive health measures. For optimal fertility, animals need additional care and optimal nutrition during the period before and after parturition (Morsy *et al.*, 2021). Animals are required to be vaccinated and received appropriate boosters for endemic diseases that may cause early embryonic mortality and abortion. There should be better training for pregnancy confirmation by transrectal palpation and encouragement of animal holders to conduct pregnancy test in cattle earlier days after insemination as a strategy to lower calving intervals and overall GHG emissions in the production system (FAO, 2013).

Breeding more productive animals

The replacement of low-producing animal breeds would decrease the total GHG emission budget from the herd while enhancing the farmer's outcome (FAO, 2018). Crossbreeding programs that are adaptable to climate change effects can be considered upgrading programs. Applications of the crossbreeding programs of local cattle can be an optimal option for the animal to enhance the sustainability of animal production in small farms. For example, local buffalo in north Africa will maintain productivity higher than Friesian cows due to their adaptation capacity even in the changing climate conditions. The type of animal production (beef or milk) needs to be taken into account during the application of these programs that also affect GHG emissions (FAO, 2013). In India, it has been found that carbon footprint (GHG emission in carbon dioxide equivalent per unit of product) of fresh milk production was lesser for crossbred cows (1.21 kg), followed by buffaloes (1.85 kg) and goats (2.54 kg), and was highest for indigenous cattle (2.96 kg) in India (Patra, 2017). This study suggested that the carbon footprint of livestock products in India could be reduced substantially through changes in livestock population patterns, adoption of crossbreeding programs or improved breeding technologies and status of intensification for different livestock species (Patra, 2017).

Manure management

Manure storage and processing are the sources of about 10% of GHG emissions (FAO, 2013). Manure contains chemical components that can lead to GHG emissions, e.g., organic matter that can be converted into ammonia, CH_4, and N_2O emissions.

Minimizing direct exposure to animal faces and urine before proper disposal is very critical (FAO, 2018). The level of GHG emissions from animal manure depends on the air temperature, method, and duration of storage. Many considerations can reduce the emission of these gasses from animal manure, for example, enhancing nutrient digestibility and feed efficiency, including the rapid collection and storage of animal wastes, reducing the duration of storage in the farm, especially at high temperatures, using covered storage facilities, composting of the manure, rapid incorporation of manure into the soil if it will be used as a soil fertilizer (FAO, 2013, 2018; Haque, 2018).

Conclusion and perspectives

The strategies for improving smallholder livestock production employing dietary management directly linked to changes in the ruminal fermentation such as enhancing the forage quality, changing the proportion of the diet, and adding dietary natural low-cost feed additives could not reduce GHG emissions, but also improve animal production. The improved dietary management should be based on a combination of factors including herd management, genetics and breeding, animal health, and manure management. However, the most important barriers to adopting GHG mitigation feeding systems and production systems are the lack of awareness, insufficient capital, and limited access to technology for small livestock holders. Overcoming these barriers requires enhancing the awareness of the livestock smallholders related to these strategies. Establishing farmer agriculture schools in combination with specific policy interventions, including financing mechanisms can be an innovative training extension program to deliver the needed information to these farmers. This activity will contribute to enhancing the awareness of the regional governments as well as the animal product market sectors to preserve natural resource management by producing animal products while protecting the environment and guaranteeing the elaboration of safe and healthy products.

Conflict of interest: Authors have no conflict of interest in this study.

Author's contribution: YAS: Conceptualized and wrote the manuscript; AKP: Wrote, reviewed and edited the manuscript. All authors read and approved the manuscript.

REFERENCES

Abo-Zeid HM, El-Zaiat HM, Morsy AS, Attia MFA, Abaza MA *et al.*, 2017. Effects of replacing dietary maize grains with increasing levels of sugar beet pulp on rumen fermentation constituents and performance of growing buffalo calves. Anim Feed Sci Technol, 234: 128-138, doi: 10.1016/j.anifeedsci.2017.09.011

Ates S, Cicek H, Bell LW, Norman HC, Mayberry DE *et al.*, 2018. Sustainable development of smallholder crop-livestock farming in developing countries. IOP Conf Ser, Earth Environ Sci, 142: 012076, doi: 10.1088/1755-1315/142/1/012076

Baylis M and Githeko AK, 2006. The effects of climate change on infectious diseases of animals. Report for the foresight project on detection of infectious diseases. Department of Trade and Industry, UK Government, pp 35

Beauchemin KA, Ungerfeld EM, Abdalla AL, Alvarez C, Arndt C *et al.*, 2022. Invited review: Current enteric methane mitigation options. J Dairy Sci, 105(12): 9297-9326, doi: 10.3168/jds.2022-22091

Boadi DA, Wittenberg KM, Scott SL, Burton DS, Buckley K *et al.*, 2004. Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. Can J Anim Sci, 84: 445-453, doi: 10.4141/A03-079

Caro D, Davis SJ, Bastianoni S and Caldeira K, 2014. Global and regional trends in greenhouse gas emissions from livestock. Climatic Chang, 126: 203-216, doi: 10.1007/s10584-014-1197-x

Eckard RJ, Grainger C and De Klein CAM, 2010. Options for the abatement of methane and nitrous oxide from ruminant production. Livest Sci, 130: 47-56, doi: 10.1016/j.livsci.2010.02.010

Eugène M, Klumpp K and Sauvant D, 2021. Methane mitigating options with forages fed to ruminants. Grass Forage Sci,76: 196-204, doi: 10.1111/gfs.12540

FAO, 2013. Food and Agriculture Organization (FAO), 2013. Climate-smart agriculture source book. FAO, Rome

FAO, 2018. Ministry of Agriculture, Livestock and Fisheries.Climate Smart Agriculture - Training Manual for Extension Agents in Kenya

FAO, 2022. FAOSTAT Database. Available at: https: / / www.fao .org/ faostat/ en/ #search/ grassland [Accessed on 26.-1.2-022]

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C *et al.*, 2013. Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. FAO, Rome

Haque M, 2018. Dietary manipulation: A sustainable way to mitigate methane emissions from ruminants. J Anim Sci Technol, 60: 15, doi: 10.1186/s40781-018-0175-7

Hoglund-Isaksson L, 2012. Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs. Atmos Chem Phys, 12: 9079-9096, doi: 10.5194/acp-12-9079-2012

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group One to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK *et al.*, (eds)]. Cambridge University Press, Cambridge, UK and NY, pp 1535

Jayanegara A,Togtokhbayar N, Makkar HPS and Becker K, 2009. Tannins determined by various methods as predictors of methane production reduction potential of plants by an *in vitro* rumen fermentation system. Anim Feed Sci Technol, 150: 230-237, doi: 10.1016/j.anifeedsci.2008.10.011

Kaufmann R, Mayer R, Schallhart N and Erschbamer B, 2021 Effects of climate change vs. grazing exclusion on species diversity over 18 years along an elevation gradient in the European Alps. Front Ecol Evol, 9: 640103, doi: 10.3389/fevo.2021.640103

McAllister TA, Okine EK, Mathison GW and Cheng KJ, 1996. Dietary environmental and microbiological aspects of methane production in ruminants. Can J Anim Sci, 76: 231-243, doi: 10.4141/cjas96-035

Morsy AS, Soltan YA, El-Zaiat HM, Alencar SM and Abdalla AL, 2021. Role of bee propolis extract on diet digestibility, purine derivatives, mitigating methane formation, and blood metabolites in late pregnant ewes. Anim Feed Sci Technol, 273: 114834, doi: 10.1016/j.anifeedsci.2021.114834

Patra A, Park T, Kim M and Yu Z, 2017. Rumen methanogens and mitigation of methane emission by anti-methanogenic compounds and substances. J Anim Sci Biotechnol, 8: 13, doi: 10.1186/s40104-017-0145-9

Patra AK and Lalhriatpuii M, 2016. Development of statistical models for prediction of enteric methane emission from goats using nutrient composition and intake variables. Agric Ecosyst Environ, 215: 89-99, doi: 10.1016/j.agee.2015.09.018

Patra AK, 2012. The use of live yeast products as microbial feed additives in ruminant nutrition.

Asian J Anim Vet Adv, 7: 366-375, doi: 10.3923/ajava.2012.366.375

Patra AK, 2014. Trends and projected estimates of GHG emissions from Indian livestock in comparisons with GHG emissions from world and developing countries. Asian-Aust J Anim Sci, 27: 592-599, doi: 10.5713/ajas.2013.13342

Patra AK, 2016. Recent advances in measurement and dietary mitigation of enteric methane emissions in ruminants. Front Vet Sci, 3: 39, doi: 10.3389/fvets.2016.00039

Patra AK, 2017. Accounting methane and nitrous oxide emissions, and carbon footprints of livestock food products in different states of India. J Clean Prod, 162: 678-686, doi: 10.1016/j.jclepro.2017.06.096

Rodríguez RM, Castrillo MC and Fondevila M, 2010. *In vitro* rumen fermentation of the tropical grass *Pennisetumpur pureum* and mixtures with browse legumes: effects of tannin contents. J Anim Physiol Anim Nutr, 94: 696-705, doi: 10.1111/j.1439-0396.2010.01001.x

Rojas-Downing MM, Nejadhashemi AP, Harrigan T and Woznicki SA, 2017. Climate change and livestock: impacts, adaptation, and mitigation. Climate Risk Manag, 16: 145-163, doi: 10.1016/j.crm.2017.02.001

Soltan Y, Adibe FAA, Abdalla A, Berenchtein B, Schiavinatto P *et al*., 2021a. Replacing maize with low tannin sorghum grains: lamb growth performance, microbial protein synthesis and enteric methane production. Anim Prod Sci, 61: 1348-1355, doi: 10.1071/AN20605

Soltan Y, Morsy A, Hashem N, Elazab M, Sultan M *et al*., 2021b. Modified nano-montmorillonite and monensin modulate *in vitro* ruminal fermentation, nutrient degradability, and methanogenesis differently. Animal, 11: 3005, doi: 10.3390/ani11103005

Soltan YA and Patra AK, 2020. Bee propolis as a natural feed additive: bioactive compounds and effects on ruminal fermentation pattern as well as productivity of ruminants. Indian J Anim Health, 59: 50-61, doi: 10.36062/ijah.59.2SPL.2020.50-61

Soltan YA and Patra AK, 2021. Ruminal microbiome manipulation to improve fermentation efficiency in ruminants. Anim Feed Sci Nutr Prod, Health Environ (Ed, AK Patra), Intech Open, doi: 10.5772/intechopen.101582

Soltan YA, Abdalla AL, Silva LRF, Natel AS, Morsy AS *et al*., 2013. Response of different tropical pasture grass species to treatment with fibrolytic enzymes in terms of *in vitro* ruminal nutrient degradation and methanogenesis. Anim Nut Feed Technol (Spl), 13: 551-568

Soltan AS, Morsy AS, Sallam SMA, Louvandini H and Abdalla AL, 2012. Comparative *in vitro* evaluation of forage legumes (prosopis, acacia, atriplex, and leucaena) on ruminal fermentation and methanogenesis. J Anim Feed Sci, 21: 759-772, doi: 10.22358/jafs/66148/2012

Soltan YA, Hashem NM, Morsy AS, El-Azrak KM, Nour El-Din A *et al*., 2018. Comparative effects of *Moringa oleifera* root bark and monensin supplementations on ruminal fermentation, nutrient digestibility and growth performance of growing lambs. Anim Feed Sci Technol, 235: 189-201, doi: 10.1016/j.anifeedsci.2017.11.021

SoltanY, El-Zaiat H, Morsy A, Hashem N, El-Azrak K *et al*., 2019. Ruminal fermentation and methane mitigation of salt tolerant Mediterranean shrubs in relation to their phenolics. At the 7th GGAA - Greenhouse Gas and Animal Agriculture Conference, August 4th to 10th at Foz do Iguassu, Brazil.

Wang C, Liu Q, Guo G, Huo WJ, Zhang YL *et al*., 2016. Effects of substituting corn with steam-flaked sorghum on growth, digestion and blood metabolites in young cattle fed feedlot diets. Anim Pro Sci, 58: 299-306, doi: 10.1071/AN16265

Wang W, Patra AK, Puchala R, Ribeiro L, Gipson TA *et al*., 2022. Effects of dietary inclusion of sericea lespedeza hay on feed intake, digestion, nutrient utilization, growth performance, and ruminal fermentation and methane emission of alpine doelings and katahdin ewe lambs. Animal, 12(16): 2064, doi: 10.3390/ani12162064

Zhang SJ, Chaudhry AS, Ramdani D, Osman A, Guo XF *et al*., 2016. Chemical composition and *in vitro* fermentation characteristics of high sugar forage sorghum as an alternative to forage maize for silage making in Tarim Basin, China. J Integr Agric, 15: 175-182, doi: 10.1016/S2095-3119(14)60939-4

Received- 28.10.2022, Accepted- 26.11.2022, Published- 01.12.2022 (Print)
Section Editor: Dr. T. K. Sar, Member, Editorial Board