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Review article

Climate change and dairy farming sustainability; a causal loop paradox and its mitigation scenario

Putri Kusuma Astuti [a,b,c,1], Afsal Ayoob [d,1], Péter Strausz [e], Beena Vakayil [d], S Hari Kumar [d], Szilvia Kusza [a,*]

[a] Centre for Agricultural Genomics and Biotechnology, University of Debrecen, 4032, Hungary
[b] Doctoral School of Animal Science, University of Debrecen, Debrecen, 4032, Hungary
[c] Department of Animal Breeding and Reproduction, Faculty of Animal Science, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
[d] Centre for Animal Adaptation to Environment and Climate Change Studies, Kerala Veterinary and Animal Sciences University, Thrissur, 680651, Kerala, India
[e] Department of Management and Organization, Institute of Management, Corvinus University of Budapest, 1093, Budapest, Hungary

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ABSTRACT

It is arguable at this time whether climate change is a cause or effect of the disruption in dairy farming. Climate change drastically affects the productive performance of livestock, including milk and meat production, and this could be attributed to the deviation of energy resources towards adaptive mechanisms. However, livestock farming also contributes substantially to the existing greenhouse gas pool, which is the causal of the climate change. We gathered relevant information from the recent publication and reviewed it to elaborate on sustainable dairy farming management in a changing climatic scenario, and efforts are needed to gather this material to develop methods that could help to overcome the adversities associated with livestock industries. We summarize the intervention points to reverse these adversities, such as application of genetic technology, nutrition intervention, utilization of chemical inhibitors, immunization, and application of metagenomics, which may help to sustain farm animal production in the changing climate scenario.

1. Introduction

Climate has been changing worldwide, and its fluctuations are predicted to be highly dynamic in the near future. The world's foremost scientific community bringing together climate change-related issues concluded that warming of the climate system is unequivocal and the significant rise in global average temperatures is overwhelmingly due to the extreme contribution of anthropogenic greenhouse gas (GHG) emissions [1]. The overabundant production and accumulation of GHG in the atmosphere contribute to alterations in global climate patterns. In the report on GHG emissions of all world country by Ref. [2], it is stated that the global GHG emissions per capita had a little increase of 0.4 % in 2022. This brings the overall growth in emissions between 1990 and 2022 to 8.3 %, with the per capita emissions rising from 6.24 t CO2eq/cap to 6.76 t CO2eq/cap. This leads to increasing the average temperature of the earth; at 0.86 °C over the 20th-century average of 13.9 °C, 2022 ranked as the sixth warmest year since worldwide records began in

* Corresponding author.
E-mail address: kusza@agr.unideb.hu (S. Kusza).
[1] Both authors contributed equally.

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1880. Over the last century, atmospheric carbon dioxide concentrations have increased from a pre-industrial value of 278 ppm–415 ppm, and the average global temperature has increased by 0.74 °C. According to the IPCC's projections, global warming will continue to accelerate in the 21st century quite alarmingly [3,4]. The effects of climate change will cause alterations in temperature, precipitation, humidity, and atmospheric CO_2 levels, will reduce water availability, and will finally result in the reduction of agricultural production [1].

The world has to deal with the significant challenge of maintaining its rapid economic expansion while addressing the global issue of climate change. The latter is mostly attributed to the excessive release of GHG into the atmosphere as a result of prolonged and intensive industrial expansion, as well as the activities in other sectors such as agricultural and livestock production. The fluctuating conditions have the potential to modify the geographical distribution and quality of diverse natural resources, hence negatively impacting the means of livelihood, such as agricultural and livestock farming [5]. The future of the sustainable development pathway is predicted mainly in correlation with its unique resource endowments, its adherence to its civilizational legacy and the maintenance of ecological balance. The climate system has undergone unprecedented changes over the past decades, which include extreme events such as drought, flood, ocean acidification, sea level rise, melting of glaciers, changes in the rainfall pattern, infestations of epidemic diseases, and threats to food security [6]. The agricultural community may also be affected by changes in temperature and rainfall patterns. These changes, along with other natural incidents caused by climate change, can speed up the extinction of many species and the destruction of their habitats [7].

The livestock industry is one of the most important agricultural sectors, contributing immensely to the global economy. Besides, livestock farming also represents a significant use of natural resources and is mainly associated with extensive land degradation and over-exploitation of water resources. Livestock is considered the oldest wealth resource of mankind, and it has also played a vital role in providing nutritious food to humans worldwide. It is the major sector that accounts for 40 % of the world's agriculture Gross Domestic Product (GDP). At the same time, it has emerged as the most important sector contributing immensely to GHG emissions [8]. Livestock systems are also inevitably affected by the newly emerging extreme climate variability, which further affects the livelihood of poor and marginal farmers [9]. Improving efficiency and productivity in agriculture, including livestock farming, is essential for maintaining environmental sustainability and economic prosperity [10], as well as ensuring global food security and human health [11].

GHG emissions have become the most discussed issue in the world due to their increasing contribution to global warming and climate change. Livestock-related GHG emissions account for about 60 % of the total agricultural GHG emissions, mainly methane and nitrous oxide. Global GHG emissions from ruminants have been estimated to be 7.1 Gt CO2 eq yr-1, representing 14.5 % of total anthropogenic contributions [12]. In addition, ruminants like dairy and beef cattle contribute significantly to livestock-related GHG emissions.

In response to climate action, the major countries, mainly those that depend on agricultural production, have taken significant steps to mitigate methane emissions from the livestock sector. In many developing countries, livestock farming plays a crucial part in ensuring the nation's food supply. While many developed countries once considered food security a "solved" problem, this is no longer the case. The cumulative effect of these interrelated problems is putting enormous strain on the planet's resources. To sustainably and ethically provide the growing demand for livestock products, we need cutting-edge animal research. Some studies report that most developed countries have successfully lowered methane emissions due to their higher productivity of animals and curtail emissions from other sectors with advanced use of methane mitigation strategies [13,14]. The developing country is not yet at that stage, although the extent of progress varies depending on the country's technology use and access. Furthermore, it becomes worse by the fact that in developing nations, there are anticipated substantial rises in livestock production. These increases are mostly driven by the growth in per capita income and/or population [15,16].

Implementation of different strategies to mitigate enteric CH_4 must consider the effects of GHG emissions from the agricultural sectors, particularly livestock. However, the cost of implementing various adaptive and mitigation strategies is very expensive, particularly in developing countries. On the other hand, the effective implementation of suitable strategies will move toward the growth of the global livestock sector in its bid to meet the increasing demand for livestock-derived products. Moreover, different livestock systems represent different capacities to adapt and require specific strategies for promoting sustainable livestock production. Furthermore, the adoption of mitigation techniques will be determined by a variety of factors, including the feasibility of adopting the strategy [17–19].

Significant gains in livestock productivity and reductions in methane emissions require the coordinated efforts of scientists from other disciplines, as well as the active participation of livestock producers. This review is an attempt to compile all available knowledge on the two-way relationship between climate change and livestock farming to uncover the hidden and unexplored complexities of this relationship. Subsequently, we evaluate the pivotal point and the viability of implementing measures to alleviate its adverse effects. Furthermore, this discussion provides a thorough examination of intervention strategies designed to effectively mitigate the harmful impacts of climate change on dairy farming productivity, with the primary objective of preventing the worsening of the current climate change situation. Furthermore, a detailed investigation is conducted to elaborate on measures aimed at improving the climate resilience of livestock farming. The detailed and comprehensive information provided by this analytical framework enhances and updates the existing knowledge about the complex relationship between livestock farming, climate change dynamics, and the necessary interventions to mitigate its impact. This helps prevent the occurrence of more severe climate crises in the future.

2. Contributions of the dairy farming sector to climate change

The livestock sector contributes a major fraction, an estimated amount of 7.1 gigatonnes CO_2-eq per annum, to global GHG emissions. Of this amount, dairy farming, including milk and meat production, accounts for the majority of emissions when compared to pigs and poultry. The contribution of the livestock sector to climatic change is realized through feed production (45 %) and enteric fermentation (39 %) [20]. Moreover, the transportation and processing of animal-derived products and changes in land use also contribute to GHG emissions [21].

Emission occurs both directly and indirectly, which mainly depends on the type of animal, population size, treatment, manure storage, and land use management [12]. Enteric fermentation, respiration, and excretions are the major sources of direct emission of methane [22]. Likewise, farm management practices, processing of livestock products, and transportation contribute to indirect emissions. In the livestock sector, indirect emissions play a more important role in the release of carbon into the atmosphere than direct emissions [23].

Enteric fermentation is the basis of the digestive process of ruminant animals; plant biomass in the rumen gets fermented and broken down by the action of microbes. The gaseous waste products of enteric fermentation, such as carbon dioxide and methane, are mainly removed from the rumen by eructation [24]. In addition, the emission rate of enteric methane varies according to feed intake and digestibility [25]. Most of the enteric CH_4 (77 %) is emitted by cattle, followed by buffalos (13 %) and small ruminants (10 %) (Gerber et al., 2013a; Gerber et al., 2013b). The quantity of gases emitted is mainly correlated to differences in environmental conditions, type of management, and composition of the manure. The organic matter content and nitrogen content of excreta influence the emission of methane and nitrous oxide (Monteny et al., 2001). During storage and processing, nitrogen is mostly released into the atmosphere as ammonia, which can later be converted to N_2O [20,26]. Also, the rate of emission increases with longer storage periods and changes in climatic conditions. Higher concentrations of these gases might be due to the lower efficiency and productivity of farm animals by causing excessive loss of nutrients, energy, and organic matter [22].

Furthermore, nitrogen fixation and atmospheric nitrogen deposition generally increase GHG emissions [27]. The manufacturing process of fertilizers contributes more than 40 million tons of CO_2 annually to the amount of GHG released to the atmosphere [20]. Similarly, ammonia volatilization loss from synthetic nitrogen fertilizers is an indirect contributor to GHG emissions. There are reports available showing that more than half of fossil fuel use can be attributed to feed production. CO_2 emissions from on-farm fossil fuel use amount to twice the quantity produced by manufacturing N fertilizers and account for 90 million tons of CO_2 per year [28,29].

The impact of different factors contributing to GHG emissions from the livestock sector has already been reviewed in the literature; however, these factors are outlined in Fig. 1 for a quick review.

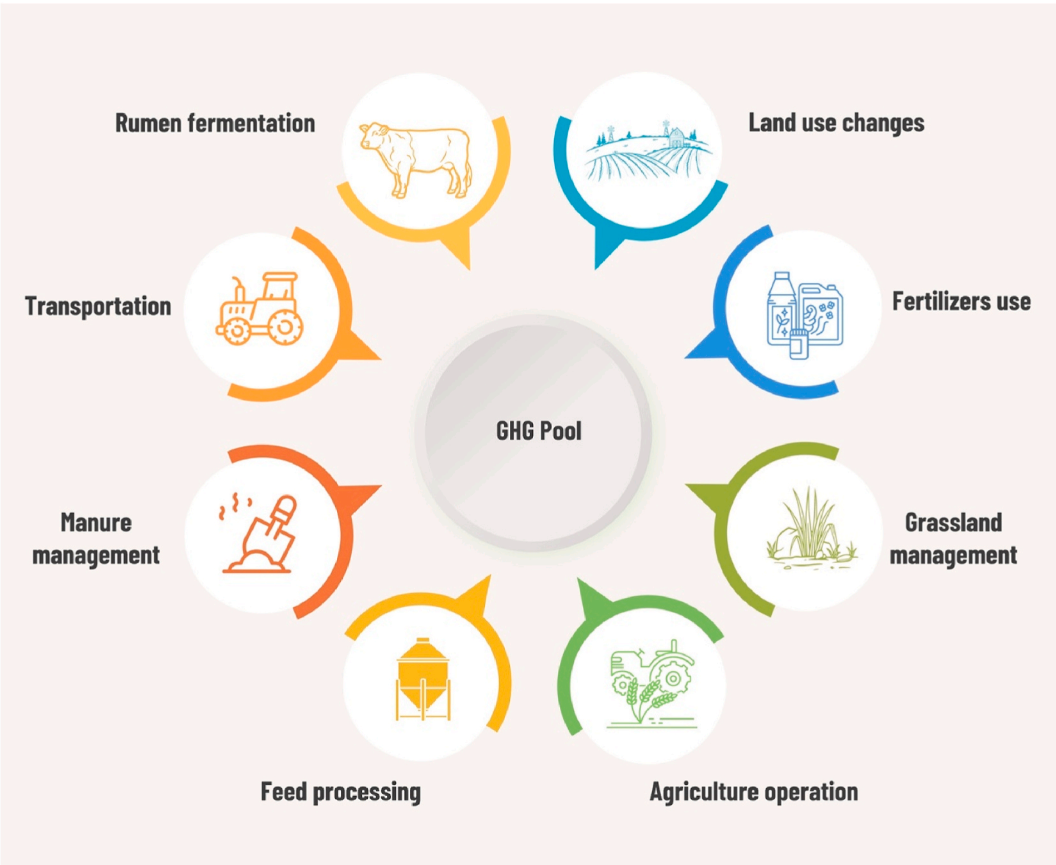

Fig. 1. The role of the livestock industry in the greenhouse gas emissions pool (these concepts were adopted from Refs. [8,26].

Optimization of GHG from the livestock sector is critical in this changing climate scenario (Fig. 2). The contribution will likely continue over the next few decades due to growing demands for meat and milk products, which are mainly driven by the increase in the human population [30]. Concerns over the tangible contribution of livestock farming to global warming have urged various studies to develop advanced scientific technologies to mitigate the global GHG emissions from ruminant animals [31].

3. The effect of climate change to the dairy productions

The long-lasting adverse physiological effect of climate change, especially the thermal stress, results in a tremendous economic loss for the dairy industry [32]. Animals adapt to thermal stress by turning on certain body mechanisms to reduce their heat production and enhance heat dissipation [33]. Such as high respiration rate, sweating, increased core body temperature, skin temperature, reduced dry matter intake and metabolism, vasodilation with increased blood flow to the skin surface, and altered efficiency of feed utilization and water metabolism [34]. This coping mechanism altered the physiological and biochemical processes inside their body, including their immunity and microbiota composition [35], which further affected the productivity of the animals.

Reduced feed intake due to HS, which is and is an ultimate sign of the HS, is hypothesized to be an initial reaction leading to lower milk production; it is often associated with negative energy balance (NEBAL), bodyweight loss, and high non-esterified fatty acids (NEFA) levels. However, another research has shown that decreased feed intake only accounts for roughly 35 % of the milk production decline caused by HS. Changes in the nutrient distribution in the body that are unrelated to dietary intake are a primary effect of HS [36–38].

Under heat stress, cows produced significantly less milk yield, less fat, protein, and energy-corrected milk, and lower fat and protein concentrations. Milk production is inhibited by HS through direct and indirect mechanisms [39,40]. The average milk yield dropped by 2.2 kg among Friesian Holstein exposed to THI values of 65 or higher [41] and by 21 % in a Mediterranean environment when the THI value scaled from 68 to 78 [42]. In addition to impacting animals during the lactation period, heat-stressed cows also exhibit changes in postabsorptive metabolism during the dry season, leading to a subsequent reduction in milk production to around 5–7.5 kg per day in the subsequent lactation period [43]. In addition to that [44], have proposed that the absence of heat stress mitigation measures for cows during the dry period could result in economic losses exceeding $800 million annually for the United States dairy industry. The dry period is an important phase for the involution of the mammary gland, while during HS, *IGF1R* serves a crucial role in cell growth and is downregulated. Despite the fact that cell loss predominates as involution advances, it is evident that there is also a component of proliferation during this early arid period, which is hindered by HS [45].

The mammary gland's ability to use nutrients and produce milk may be impaired by the alterations in energy metabolism caused by HS, as the hypothalamic-pituitary-endocrine axis, which regulates key functions like stress response and lactation, becomes unbalanced in the presence of HS [40]. Milk yield (quantity) and milk component (quality) are highly related, though milk components are

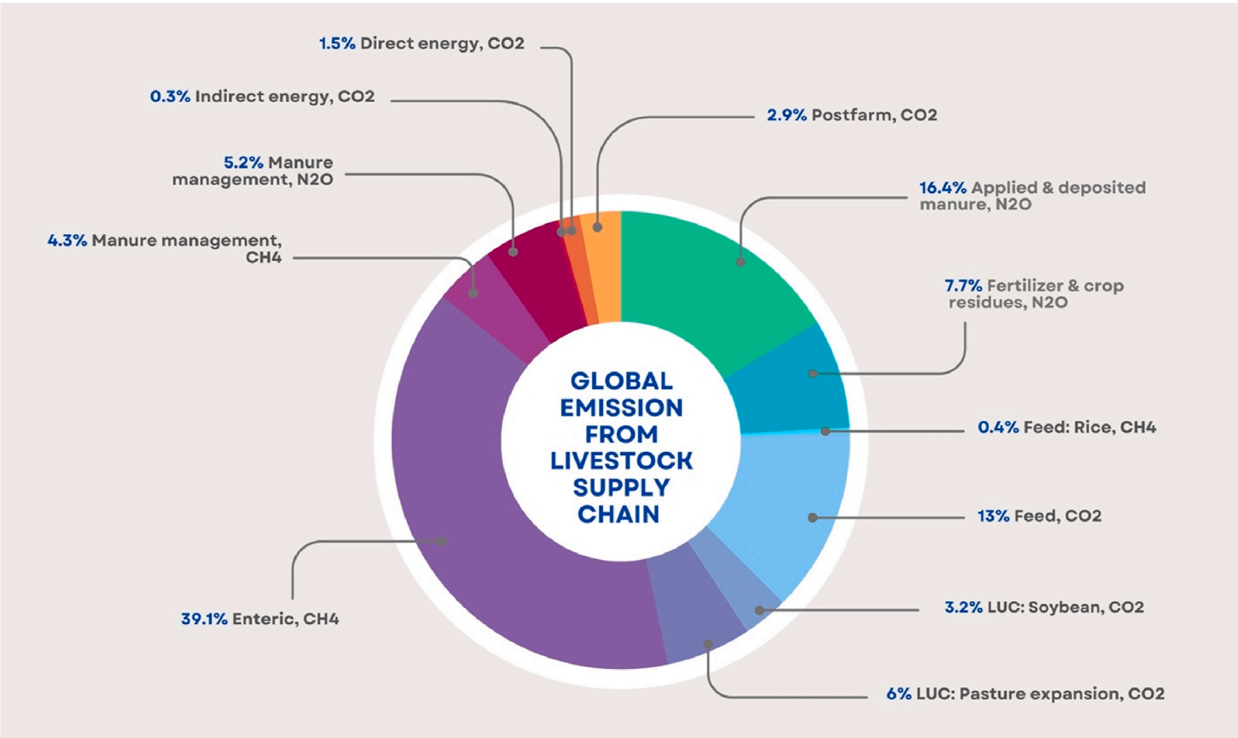

Fig. 2. The FAO Report [26] highlights the impact of the livestock supply chain on world emissions. LUC = land usage change.

more sensitive to heat stress than milk yield, according to research on the dairy business in the Canadian environment. A potential annual economic loss of $34.5 million attributable to heat stress in Ontario and Quebec is based on a THI threshold of 58 for fat and protein yields in dairy cattle and an average of 156 days a year with an average of 10 THI units over the threshold [46]. In the case of the UK, the average daily temperature is expected to rise by 4°Celsius by the end of the century, causing economic loss between £2000 and £6000 per year in income in average years and between £6000 and £14,000 per year in extreme years for average-sized dairy farms [47]. This economic loss is due to HS's direct effect on milk production, as well as the cattle's declining immunity and increasing pathogen challenge due to disease survival and proliferation aided by high temperatures, which increases susceptibility to infections and affects udder health [48].

Let us begin with normal circumstances before going deeper into the extreme climate change scenario; environmental infections thrive in the hot and humid conditions of summer. Seasonal influences on the incidence rate of clinical mastitis caused by several infections have been recorded [49]. According to Ref. [50], the incidence rate of clinical mastitis for *Streptococcus uberis* was highest in summer, whereas other infections, such as *Staphylococcus aureus*, *Escherichia coli,* and *Streptococcus dysgalactiae*, were more likely to develop in winter. When the THI was raised from 72 to 78, a case in Egyptian cattle milk showed an increase in SCC, total cell count, fecal cell count, and *Escherichia coli* count [51]. In addition, the rate at which *Staphylococcus aureus* and *Escherichia coli* were isolated from the milk of cows exposed to THI values higher than 72 began to rise dramatically [52]. The occurrence of metritis in cattle may exhibit an upward trend during episodes of heat stress. The occurrence of heat stress in the later stages of gestation has the potential to inhibit the uterine defense mechanisms, hence contributing to the manifestation of uterine disorders such as metritis. This condition can result in decreased fertilization rates, impaired early embryonic development, and an elevated likelihood of pregnancy loss [53].

4. Major mitigation strategies used for curtailing GHG emission from livestock

4.1. Nutritional intervention

Nutritional technologies paved the way for reducing GHG emissions by their practical utility and simplicity. Feed manipulation involves supplying concentrate, antibiotics, plant secondary metabolites, organic acids, and chemical inhibitors [54]. Providing concentrate within the feed diet is negatively correlated with methanogenesis in ruminant animals. Also, increasing the proportion of starch in the diet can alter the concentration of volatile fatty acids, i.e., propionate rather than acetate concentration increases. Furthermore, this will help to reduce the hydrogen supply for CH_4 production [55]. Several studies show that increased propionate concentration can reduce the rumen pH and inhibit the activity of methanogens [56,57]. In addition, ionophores, which are used in animal rations to improve milk production [58], also have the ability to depress CH_4 production. Recent studies show that the inhibition of methanogenesis by ionophores cannot persist over a longer period of time. Vegetables and animal lipids are used in animal rations to enhance their productivity. Supplementation of dietary lipids promotes the synthesis of more propionate, resulting in lower methane production. This effect was attributed to the biohydrogenation of unsaturated fatty acids, which utilize hydrogen, potentially decreasing methanogenesis [59]. Methanogenesis has been effectively reduced by adding lipids to ruminant diets, and it is estimated that supplying lipids can reduce methane production by a rate of 4–5 % (g/kg DMI) for every 1 % increase in the lipid content of the diet. However, the oversupply of lipids (fat) (above 7 %) can reduce feed intake and the digestion process in animals. Furthermore, it will affect various productive functions in animals and result in lower milk production [60]. In addition, soya bean oil, canola oil, and coconut oil are also widely used for controlling methane production by 19–62 % in different ruminant animals [61]. The supplementation of dietary oils such as sunflower oil in ruminant diets can provide effective improvements in terms of efficient milk/meat production and reduction of GHG emissions. The usage of sunflower oil in animal rations can effectively reduce rumen fermentation to a level of 11.5–22 % [62].

4.2. Plant secondary metabolites

Tannins, saponins, and phenolic monomers are toxic to microbial populations and, thus, may help in reducing methanogenesis. Tannins may decrease CH_4 directly by inhibiting methanogenic bacteria and indirectly by decreasing the synthesis of hydrogen as a result of indigestion of fiber and microbial density in the rumen [63]. [20], denoted that the amount of enteric methane is reduced by the introduction of tannin-rich diets which possess the anti-methanogenic activity, either by direct inhibition of methanogens or indirectly through inhibition of protozoa. Tannins are polyphenolic compounds that bind to proteins and can be used as chemical additives to reduce the ruminal fermentation of animal proteins. The binary combination of nitrate and quillaja saponin inhibited methanogens effectively in an in vitro rumen culture by 32 % at 5 mM nitrate and 0.6 g/L saponin, and by 58 % at 10 mM nitrate and 1.2 g/L saponin [31]. Saponins inhibit rumen protozoa, which contributes to the inhibition of hydrogen production and reduction of the abundance of methanogens. Nitrate functions as a strong electron sink that outcompetes CO_2 for electrons. Furthermore, nitrate reduction is directly toxic to methanogenic bacteria [64]. Forages contain several plant secondary metabolites, and plant extracts containing tannins, saponin, and phenolic monomers are toxic to some rumen microbes, especially ciliate protozoa, fiber-degrading bacteria, and methanogenic archaea, reducing enteric fermentation in ruminants [65].

4.3. Use of chemical inhibitors

There are several chemical compounds that have the ability to inhibit methane production in ruminant animals. Halogenated methane compounds, such as chloral hydrate, amichloral, bromochloromethane, nitroethane, and 2-nitropropanol are examples of potential methanogenesis inhibitors. In addition, bromochloromethane can inhibit methanogenesis by reacting with coenzyme B, which acts on the final step of the methanogenic pathway [66]. In summary, dietary manipulation provides many viable options for reducing GHG emissions from the livestock sector. Apart from this, the doses of dietary manipulators found in several in vitro and in vivo experiments are different. Also, the dry matter content of the rumen may vary by 10–25 % depending on several factors, which was found in most of the scientific results [67]. Moreover, increased usage of dietary chemical inhibitors might affect feed digestion and milk production. In addition, as pointed out by most pertinent studies, ruminants' reduction in methane production due to diet management is short-term and mainly focused on methane emissions. Future research should be taken up to analyze the long-term impacts of methane emissions from the entire livestock farm and to develop tangible strategic measures to reduce GHG emissions [68,69].

4.4. Application of genetic technologies: RFI as a nutritional tool

GHG from the livestock sector is directly proportional to the number of animals in the entire farm. In this manner, the application of new technologies, including genetic breeding and advanced reproductive technologies, will play an important role in mitigating challenges faced by the livestock sector. Genetic improvement of livestock is a particularly cost-effective technology that produces permanent and productive changes in ruminant animals. The greatest limitation of a breeding program lies in measuring feed intake associated with CH_4 emission [70,71]. Also, methane production from different animals under identical feeding conditions shows significant variation among the animals. RFI is defined as the net feed efficiency, which is used as a tool for measuring the productive efficiency and methane emission in farm animals [72]. The sudden increase in the prices of feeding resources could urge the farmers to focus mainly on feed efficiency and productivity in farm animals. Moreover, analyzing a large amount of feed intake data of individual animals could be effectively used in identifying the appropriate adaptive and amelioration strategies [73]. It will also help in identifying the genomic traits which can be used marker-assisted breeding program for producing better animal breeds [74]. Recent research has demonstrated that, animals with lower residual feed intake (RFI) for their body maintenance and production would emit less CH_4 than animals with high RFI values [75]. Overall, the reduced RFI in dairy animals probably results in improved fermentation and digestibility of nutrients and became more efficient in their productivity [76]. This may offer an opportunity for genetic selection for this trait, and it can be selected without compromising the production traits [77]. It has also been suggested that greater suppression of CH_4 could be achieved by low-digestibility diets when animals are selected based on low RFI [78]. Genomic traits related to productive efficiency are dry matter intake (DMI), RFI, and methane emission, which can be effectively considered in a genetic breeding program. Resource use efficiency phenotypes are very difficult and expensive to analyze, but genomic selection is a promising tool to facilitate the selection of the most productive farm animal. By applying genomic selection, a reduction in predicted CH_4 (g/d) of 15 % in 10 years is theoretically possible [79]. Thus, the strategy can be effectively used for suppressing methane production in tropical countries, where low-quality feeds are fed to ruminants. According to Pryce et al. [79], the accuracy of genomic predictions of RFI, energy balance, and DMI ranged between 0.20 and 0.43 in farm animals. In addition, reductions in methane emissions were found in dairy cattle at a range of 13.45 g CH_4/kg RFI and 18.2 g CH_4/kg RFI [75]. Recommendations for advanced genetic and mitigation strategies would result in enhanced animal productivity and feed efficiency with metabolic modifiers such as rbST, and growth promoters would also reduce GHG emission [80]. Moreover, direct methane measurement is an expensive and time-consuming approach for gathering significant amounts of data from a large number of animals. Collecting these types of data from different regions could assist in modifying the amelioration strategies and give a clear-cut picture of methane emissions in various environments. Such systems might be an attractive way to exploit the genetic variation in RFI, and manipulating the traits associated with GHG emission is of great economic importance for farm animal production. However, the precision and robustness of this method still need to be enhanced and verified in other environments by doing proper research [81,82].

4.5. Immunization: a biological approach

Immunization is one of the biological tools applicable to optimizing methane production. It offers a wide and diverse solution to the problems associated with animal health [66]. The most important vaccines in this field can be used as target tools against specific methanogens [30]. Such a vaccine was effectively used in sheep with a mixed whole-cell preparation from three methanogens, resulting in CH4 production reduced by 7.7 % (gram per kilogram of dry matter intake) [83]. Ruminal microbial urease plays a pivotal role in the nitrogen metabolism of ruminant animals. Similarly, the urease enzyme present in the animal fecal matter hydrolyses urea to ammonia. It is the major pool for nitrogen production by many ruminal bacteria, including cellulolytic bacteria. Also, the immunized cows were repeatedly vaccinated with the vaccine called UreC of *H. pylori*. Moreover, the vaccinated cows significantly reduced the urease activity by 17 %, subsequently, the fourth booster [84]. Development of advanced recombinant vaccines against methanogens could be established in a broad area related to animal health. It might be a successful technology for mitigating methane production [85].

4.6. Rumen microbial metagenomics: an emerging tool

The rumen microbial population plays an integral role in enteric fermentation in ruminant animals. Identifying the microbial communities and their functions would help to manipulate the rumen characteristics for higher production and low emission [86]. Metagenomics provides a wide application in reducing methane emission, but currently, research studies are limited to isolating metagenomic DNA associated with enteric methane emission. The rumen environment is difficult to study using conventional technologies but can be effectively studied through metagenomic analysis methods [87]. These techniques will also help to understand the methanogenesis process and assess the effects of methane-reducing agents on the overall composition and function of the rumen microbial community. Furthermore, microbiome studies will pave the way for quantifying developments like rumen characteristics, animal production, tolerance to environmental stress, and resistance to pathogens, and eventually will help to reduce metabolic disorders [88]. Finally, metagenomics seems to be a potential tool for studying complex rumen characteristics, and it helps enrich our knowledge about their functioning. Furthermore, these microbiomes may also serve as sources for optimizing the pressing environmental problems associated with GHG from ruminant livestock in a multidimensional manner [89,90].

5. Pathways to promote sustainable livestock production

The concept of sustainability has commonly been framed as attainable by improving the efficiency of current operations through the application of scientific and technological advancements. Furthermore, given that environmental concerns have become a prominent factor in agricultural practices, it is imperative to acknowledge the significance of local agroecological knowledge and the variations in social and environmental contexts [91]. Fig. 3 illustrates climate-smart dairy farming and describes advanced strategies like housing, handling, and management to improve farm animal welfare by optimizing the development of a strategic foundation that can generate economic benefits while mitigating the negative effects of climate change on livestock and animal food production. This strategy has the potential to address challenges related to food security, animal odors, and the magnitude of GHG emissions [92]. One of the examples is the integrated crop-livestock system (ICLS), which might be considered a sustainable agricultural system that can contribute to increasing food security under climate change. A projected report suggests that the specialized farm net revenue falls as much as 75 % under a changing climate scenario, whereas the mixed farm net revenue falls only by 10 % for the same climate scenario [93].

6. Conclusion

The interconnection between livestock production and climate change is undeniable and remains a subject of debate, with ongoing discussions on its causal paradox. In this particular setting, the present paper provides a complete analysis of the reciprocal relationship between climate change and livestock production. Livestock production is also recognized as a prominent contributor to the emission of greenhouse gases (through rumen fermentation, land use changes, fertilizer use, grassland management, agriculture operation, feed processing, manure management, and transportation), hence exacerbating the issue of global warming. Some perspectives advocate for implementing limitations on livestock production to alleviate the detrimental impacts of climate change. Simultaneously, the global need for livestock production is steadily rising due to the growing human population and changing lifestyles. Nevertheless, severe climate conditions hinder the production of livestock by disrupting animal wellbeing, reducing productivity, compromising immunity, and increasing disease prevalence.

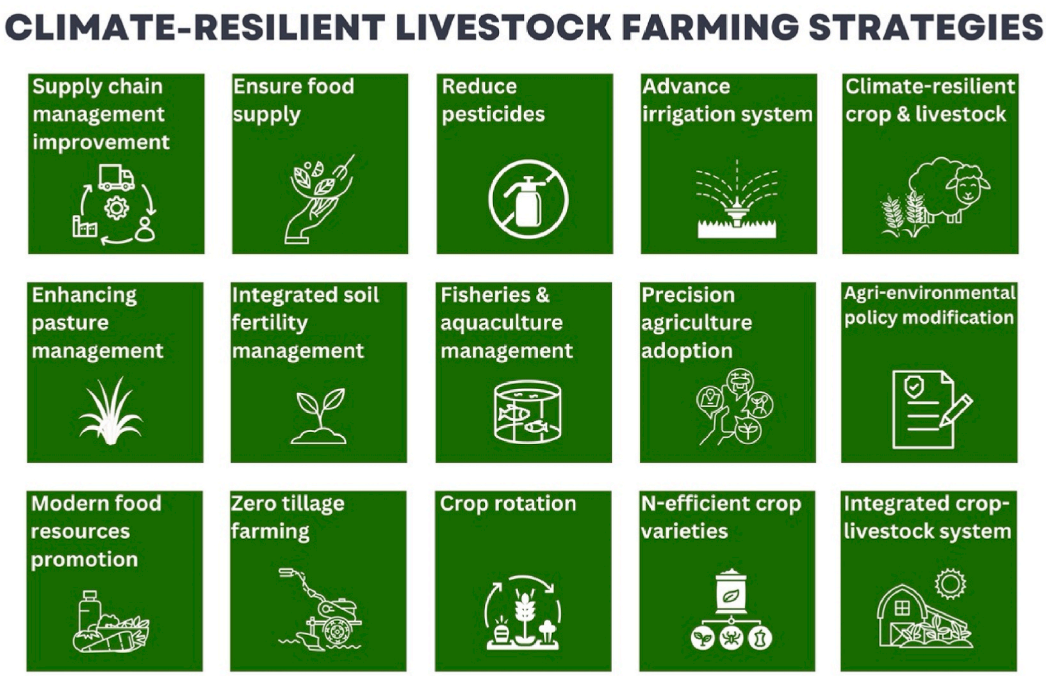

Fig. 3. Salient adaptation and amelioration strategies to sustain the climate resilient dairy farming [94].

The critical importance of achieving harmony and balance between these two fundamental elements of human existence is of utmost significance. Identifying an optimal synergy involves creating and executing methods that enable sustainable animal production while also reducing the environmental impact, particularly with regards to climate change. This entails implementing measures to decrease the environmental impact of livestock farming, including procedures such as application of genetic technology, nutritional interventions, the use of chemical inhibitors, immunization, and the application of metagenomics.

There is a pressing necessity to generate comprehensive awareness regarding climate change and variability matters. Enhancing the management of natural resources can lead to improved livestock productivity and effective mitigation of the challenges arising from climate change. One approach to achieve this is by discovering climate-resilient animals that have lower methane emissions, and improving crop and waste management. This can be facilitated by implementing and enforcing more effective agri-environmental policies.

7. Future recommendations

There are research pertaining to the impacts of climate change on livestock production has developed several strategies and tools to quantify the various environmental stress responses; the practical utility of these methods to alleviate different stress is still at stake. Further, advanced research efforts have to modify the established mitigation strategies to aid region-specific alleviation methods. Moreover, the available livestock models should be modified with the introduction of species-specific factors so as to predict a reliable projection. In addition, technological advancement has to be introduced in fields like metagenomics and transcriptomics, which provide better insight into the heat tolerance of indigenous livestock species. Accordingly, scientists should explore the scope of these techniques in developing climate-resilient breeds such that they could be disseminated to poor and marginal farmers to sustain farm animal production. Furthermore, the extended work should go hand in hand with research in order to introduce a new technologies from labs to farms. Above all, the farmers, recognized as the front-line soldiers of climate change, should be trained about the various impacts pertaining to climate change and provide awareness about the need to curtail GHG emissions associated with agricultural production. There is a need for more robust promotion of sustainable livestock farming, which can be achieved by measures such as offering subsidies to facilitate the adoption of necessary technologies or providing incentives to farmers who have successfully transitioned to a more sustainable system. Undoubtedly, an effective partnership among researchers, farmers, and the government will expedite the achievement of ecologically sustainable livestock farming.

Data availability statement

No data was used for this article.

CRediT authorship contribution statement

Putri Kusuma Astuti: Writing – original draft, Visualization, Methodology. **Afsal Ayoob:** Writing – original draft, Formal analysis, Conceptualization. **Péter Strausz:** Writing – review & editing, Investigation, Formal analysis. **Beena Vakayil:** Writing – review & editing, Formal analysis, Data curation. **S Hari Kumar:** Writing – review & editing, Methodology, Formal analysis. **Szilvia Kusza:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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