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Spatial Patterns of Greenhouse Gas Emissions in Livestock Farming and the Potential of Plant Protein Emission Reduction

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Abstract. As global climate change worsens, the substantial greenhouse gas emissions from livestock farming have emerged as a major contributor to overall greenhouse gas levels. As a result, the mitigation of livestock farming's impact on climate change has become a key global challenge. This paper investigates regional variations in greenhouse gas emissions from livestock farming and explores the potential of substituting animal protein with plant protein as an effective strategy for emission reduction. Through a comprehensive analysis of greenhouse gas emission data and relevant literature in major livestock farming regions around the world, such as North America, Latin America, East Asia and South Asia, the results indicate that large-scale breeding will lead to higher energy consumption and carbon emissions than extensive breeding. Besides, social factors, like the huge population and the high demand consumption market for cattle and sheep, have contributed to the expansion of livestock farming and further aggravated carbon emissions. Accordingly, this paper reveals that replacing animal protein with plant protein can greatly lower greenhouse gas emissions and promote low-carbon, environmentally friendly production, providing a feasible solution to climate change.

Keywords: Greenhouse Gas Emissions from Livestock Farming, Regional Variations, Livestock Type Effects, Plant-Based Protein Emission Reduction

1. Introduction

The major global environmental challenge of climate change results primarily from by emissions of greenhouse gases, including carbon dioxide, methane, and nitrous oxide. Though fossil fuel burning produces most carbon dioxide, livestock farming emits methane and nitrous oxide via overgrazing, digestion, and manure handling, and its contribution to global warming cannot be ignored. However, existing research mainly examines global or national emission totals, but regional variations, spatial distribution, and the natural and socio-economic drivers of livestock greenhouse gas emissions are still underexplored. In addition, research on the potential and feasibility of replacing animal protein with plant protein to lower greenhouse gas emissions, especially across regions and livestock types, remains limited. Therefore, this paper analyzes the overall situation of greenhouse gas emissions in global livestock farming and its regional differences, explores the impact of natural geography and

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socio-economic factors on the spatial pattern of emissions, compares the contributions of different livestock types and production systems, and evaluates the potential of replacing animal protein to reduce emissions, based on technical, economic, and social factors. Through literature review and comparative analysis, it identifies the differences between the main regions and types of livestock greenhouse gas emissions in livestock farming, and assesses the potential emission reduction from substituting plant protein, to guide livestock emission plans and boost plant protein.

2. Global greenhouse gas emissions from livestock farming and regional differences

2.1. The overall situation of global emissions

Global livestock plays a significant role in greenhouse gas emissions. Based on data from the Food and Agriculture Organization of the United Nations, in 2015, livestock-related agrifood systems, including on-farm production, feed production, transport, and input manufacturing, emitted around 620 million tonnes (Mt) of CO_2 equivalent (CO_2eq). This accounts for about 12% of global human-caused greenhouse gases and 40% of agrifood system emissions [1]. Although these emissions are much lower than the CO_2 emissions from fossil fuels, they should not be ignored. In comparison with the carbon absorption capacity of global tropical rainforests, the 620 Mt of CO_2 equivalent emitted by livestock in 2015 is roughly equal to the amount of CO_2 these forests absorb in 1.2 years, highlighting the potential influence of livestock emissions on climate change. The growth of the global population and meat consumption has led to higher livestock greenhouse gas emissions in recent years. According to the United Nations Environment Programme, global greenhouse gas emissions reached 57.1 billion tonnes of CO_2 equivalent in 2023, showing an increase compared with 2015. As the global population continues to grow, particularly in developing countries, the rising demand for meat is expected to drive further increases in livestock-related greenhouse gas emissions. This trend suggests that livestock will remain a major contributor to global greenhouse gas emissions in the coming decades.

2.2. Spatial distribution of major emission areas

There are regional variations in livestock greenhouse gas emissions. High emissions are mainly concentrated in East Asia (China), South Asia (India), North and Eastern South America, while central Eurasia, Africa, and Oceania show relatively low emissions [2]. The formation of high-emission areas is related to the large population base, the high consumption level of meat and dairy products, and the concentration of breeding patterns. High livestock emissions in East and South Asia are driven by dense populations and strong demand for meat, eggs, and dairy, which have led to rapid expansion of livestock production. In the southern United States (U.S.), high-income communities sustain large, energy-demanding livestock operations. In eastern South America, the expansion of agricultural production has involved extensive deforestation of the Amazon, increased fertilizer use, and reduced forest carbon absorption capacity, all contributing to a significant rise in the carbon footprint of livestock. Low-emission regions often have extensive natural grasslands, where livestock are raised in extensive, low-intensity systems. Thus, animals are widely dispersed, energy use is low, and concentrated greenhouse gas emissions are limited. Climate conditions and land resources also play a key role in shaping emission patterns. Warm, humid, and fertile areas promote pasture growth and improve feeding efficiency, while arid or poor soils constrain livestock production, naturally resulting in lower emissions. Consequently, global livestock greenhouse gas emissions exhibit a pattern of a few high-emission hotspots and scattered low-emission areas.

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2.3. Differences in contributions by livestock type

There are clear differences in the contribution of livestock types to greenhouse gas emissions, with cattle farming leading globally [3]. The production process of livestock farming covers many links such as feed production, livestock breeding, and livestock product processing, and these links have significant differences in emissions in different types of livestock farming. Relevant studies show that cattle farming produces the highest greenhouse gas emissions, reaching 3.844 billion tons of CO_2 equivalent, nearly 3 billion tons over pig farming, which ranks second, as shown in Figure 1 [4]. Compared with other livestock like chickens and sheep, cattle emit more methane due to their physiology and low feed efficiency. In terms of breeding methods, there are obvious differences in emissions between centralized and coarse breeding. Owing to its large scale, centralized breeding consumes more energy for power and heating, raising greenhouse gas emissions. Additionally, large centralized stocks concentrate emissions locally, hence intensifying the regional greenhouse effect. Further analysis reveals that the breeding method chosen is largely determined by management, technology, and regional factors, which directly influence emission levels. With high-efficiency management and modern technical support, the emissions of centralized farming may be suppressed to a certain extent, but the overall emissions are still higher than those of rough farming.

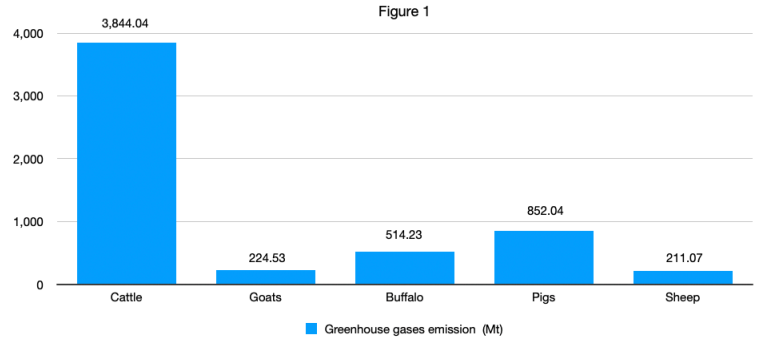

Figure 1. Differences in greenhouse gas emission contributions by livestock type

3. Causes and drivers of greenhouse gas emissions in livestock farming

3.1. The role of natural and geographical factors

The differences in greenhouse gas emissions from livestock farming across regions are mainly due to natural and geographical factors conditions [5]. Factors like climate, topography, and hydrology provide favorable environments for livestock farming, promoting its development while indirectly increasing greenhouse gas emissions. In mild and humid climates, pastures and feed crops thrive, supplying high-quality natural feed for ruminants such as cattle and sheep, which enhances feeding efficiency and enables larger-scale farming. Flat terrain supports large-scale farms and simplifies feed transport and livestock product distribution, thus leading to more concentrated greenhouse gas emissions in the region. Abundant water resources and dense river networks not only meet the water and cleaning needs of livestock but also support the transport of livestock products, further enabling the expansion of farming scale. The combined effect of these natural conditions gives regions such as East Asia, South Asia, the southern U.S., and eastern South America an advantage in livestock development, while also making them high-emission areas for greenhouse gases.

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3.2. The impact of socioeconomic factors

In addition to natural conditions, socioeconomic factors are important drivers of livestock farming emissions [6]. Factors such as population, economy, and consumption patterns directly drive global variations in livestock farming emissions. In low- and mid-latitudes, especially dense coastal cities, demand for meat, dairy, and eggs is high. This consumption demand stimulates the expansion of local livestock farming, increasing greenhouse gas emissions [7]. As economies grow and living standards improve, demand for high-protein foods and meat continues to rise. This expands farming scale and raises greenhouse gas emissions. Besides, convenient transportation makes the movement of goods between urban centers and suburbs more efficient. Market demand encourages livestock farms to develop toward large-scale and intensive operations, further increasing the concentration of emissions. Overall, socioeconomic factors, together with natural conditions, determine the regional differences and spatial patterns of greenhouse gas emissions from livestock farming.

3.3. Mechanisms of spatial pattern formation

The spatial differences in greenhouse gas emissions from livestock farming are mainly determined by natural geographic conditions and socioeconomic factors [6]. Mild and humid climates favor the growth of pastures and feed crops, providing high-quality feed for livestock such as cattle and sheep and improving feeding efficiency. Flat terrain facilitates the establishment of large-scale farms and supports the transport of feed and livestock products, with adequate water resources supporting livestock drinking and sanitation, further encouraging farm expansion. These conditions lead to concentrated livestock farming in regions such as East Asia, South Asia, southern North America, and eastern South America, resulting in relatively high greenhouse gas emissions.

In addition, socioeconomic factors also play an important role in shaping the spatial patterns of livestock farming emissions. In some wealthy and densely populated regions, particularly in parts of Asia and the Americas, strong meat demand has fueled rapid growth of livestock farming, thus raising greenhouse gas emissions. In these areas, rising consumption patterns and living standards have boosted the development of large-scale farming systems, resulting in higher emission intensity. In contrast, in less developed regions, although natural conditions may be suitable for livestock farming, limited economic resources and market demand lead to smaller-scale operations and lower greenhouse gas emissions. Besides, these spatial differences are closely related to globalization and the resulting market changes. As global trade and transport networks expand, production in high-emission regions meets world demand, further driving livestock farming growth. In particular, in developed and emerging economies, livestock farming continues to intensify with urbanization, and greenhouse gas emissions are likely to keep rising.

4. Emission reduction potential of replacing animal protein with plant protein

With the increasing impact of livestock farming emissions on climate change, plant protein has the potential to reduce greenhouse gas emissions as a substitute for animal protein. Therefore, replacing animal meat with plant meat or replacing animal protein with plant protein has become a feasible solution. In addition, plant-based can meet human nutritional needs and significantly reduce the environmental burden in production, providing a new path for climate change mitigation.

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4.1. Substitution mechanisms and underlying principles

The production process of plant meat covers many links from plant planting, transportation, protein extraction to processing and production. In these processes, the primary sources of greenhouse gas emissions are fertilizers, energy use, and transport-related carbon emissions [8]. However, plant-based meat produces significantly lower greenhouse gas emissions than traditional animal meat. First of all, the production of plant protein does not involve methane emissions from ruminants, thus avoiding greenhouse gases generated during animal digestion. Besides, less energy is used in the production of plant meat, and most plant materials (such as soybeans) have high biofixation capacity, which helps to reduce carbon footprint.As a major source of plant protein, soybeans not only contain rich full-valent protein, which can provide 9 essential amino acids needed by the human body, but also have excellent nutritional value. In addition, in the processing of plant meat, its nutritional function can be further improved by adding vitamins, minerals and other ingredients. From the standpoint of greenhouse gas emissions and nutritional supplementation, plant protein, as an alternative to animal protein, offers substantial environmental benefits and can supply all-round nutritional support for consumers.

4.2. Emission reduction potential and influencing factors

The capacity for reducing emissions through replacing animal protein with plant protein is highly promising, yet the actualization of this potential is influences by numerous factors. Regarding the greenhouse gas emissions, plant protein production emits less than animal protein production. Prior studies have shown that if 50% of animal proteins worldwide are replaced by plant proteins, the average annual greenhouse gas emissions can reduce about 6.1 Mt of CO_2eq, significantly slowing down the process of climate change [9]. Plant protein also reduces the carbon footprint by lowering agricultural methane emissions and decreasing resource use and pollution from large-scale livestock farming. In addition, with production process optimization, the emission reduction potential of plant protein is expected to increase, especially through more efficient protein extraction and plant-based meat technologies. Nevertheless, the realization of this emission reduction potential is not without challenges. Technical factors play a key role in reducing the emission of plant proteins. The current protein extraction process still consumes high energy and generates significant raw material waste in large-scale production, posing an urgent need for efficiency and energy savings. Simultaneously, progress has been made in the color, fragrance and taste of simulated animal meat, which helps to improve the market acceptance of products, expanding the scope of alternative applications. Social factors also influence the adoption of plant protein. Consumers have long relied on animal protein, and while they recognize the health and environmental benefits of plant protein, their habits change slowly. Increased public health and environmental awareness can boost acceptance and promote market growth.

4.3. Regional differences and implementation feasibility

The promotion of plant protein to replace animal protein varies across regions, which is mainly affected by economic development, technical level and social culture. In developed countries, advanced production technology and high environmental protection awareness make it relatively easy to promote plant protein. In developing countries, residents' demand for meat is still strong, and their willingness to eat plant-based meat for a long time is low. In addition, the limited level of technology makes the promotion challenging. The implementation requires holistic consideration of

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technology, resources, and social acceptance. In terms of technology, the extraction and extrusion process of plant protein has been continuously improved, which has improved the taste and texture. Some studies have optimized the soybean high-moisture tissue vegetable protein raw material formula and double-screw extrusion process parameters, affecting the texture of cooked beef. It has been found that the isolated soybean protein can improve the hardness and chewiness, and its sensory score for homemade vegetarian beef is significantly higher than that of commercial products [10]. In terms of resources, the global soybean production is sufficient. According to 2023 data, one hectare of soybeans can produce about 300 tons of plant-based meat, enough to provide 100 grams per day for a year to around 800 people [11]. Economically, initial production requires investment in research and development, production infrastructure, and marketing. However, with technological advancements and large-scale production, costs are expected to decline, reducing livestock farming's environmental costs. At the social level, consumers have limited awareness of taste and processing technology, and the acceptance is low in the short term. However, with the improvement of science and technology and the publicity of health and environmental protection, the market acceptance is expected to increase.

5. Conclusion

This paper analyzes the overall situation, regional differences and driving factors of greenhouse gas emissions in global livestock farming. The results indicate that high emissions are largely centered in East Asia, South Asia, southern North America, and eastern South America, closely linked to local population density, farming scale, and level of production intensification. Specifically, cattle farming and intensive livestock systems are the main sources of emissions, and natural geographical conditions, such as a mild and humid climate, flat terrain, and abundant water resources, as well as socioeconomic factors, like population distribution, economic level, and consumption habits, jointly shape the spatial pattern of livestock emissions. In addition, this study shows that replacing animal protein with plant-based protein has the potential to mitigate greenhouse gas emissions, particularly in developed countries where such measures can be rapidly implemented. However, in developing countries, the adoption of these strategies still faces technical, economic, and social barriers. In short, achieving emission reduction depends on improvements in production technology, rational resource utilization, and increased public awareness. The analysis presented in this study helps to identify key regions and targets for livestock emission reduction and provides a reference for the promotion of plant-based proteins and low-carbon dietary strategies.

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