From Enteric Methane to Agricultural System Rebalancing: Animal Metabolism, Pathway Accommodation, and Sustainable Agricultural Modernization

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Abstract Enteric methane from ruminants is commonly framed as a greenhouse gas emission problem to be reduced through feed additives, microbial regulation, manure treatment, or livestock management. While these approaches are necessary, this paper argues that methane should not be treated only as an emission object. Rumen methane is first a metabolic outlet formed through anaerobic fermentation, hydrogen release, carbon-flow conversion, and animal－microbial symbiosis. It becomes a governance pressure when this metabolic outlet is amplified by high-density livestock production, externalized feed dependence, concentrated manure discharge, insufficient soil accommodation, and broken energy pathways. This paper therefore proposes a shift from emission governance to pathway governance. Rather than asking only how methane can be reduced, pathway governance asks where methane originates, why the node is amplified, which downstream pathways have failed, and how metabolic products can be re-accommodated within energy, soil, biological, and regional circulation systems. The paper examines animal metabolism, rumen microbial relations, feed-pathway mismatch, stocking-density mismatch, manure-pathway mismatch, and methane-use pathways such as biogas, methanotrophs, microbial protein, synthetic fuels, and high-value conversion. It concludes that sustainable methane governance must integrate animal health, microbiome stability, manure return, soil restoration, energy recovery, and regional carrying capacity. There are no natural enemies, only pathways not yet reorganized

Keywords enteric methane; rumen metabolism; pathway governance; agricultural system rebalancing; manure accommodation; microbiome networks; sustainable agricultural modernization; livestock methane mitigation

1 Introduction: Reframing Agricultural Governance from the Position of Life Metabolism

1.1 From an emission object to a metabolic node

Discussions on methane emissions from ruminants often begin with the technical

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question of how to reduce enteric methane production. This starting point is understandable, since methane is a potent greenhouse gas and enteric fermentation is a significant issue in agricultural greenhouse gas mitigation [1-3]. Yet once rumen methane is defined at the outset as an emission object to be suppressed, reduced, or eliminated, the problem is already framed through objectification. Methane becomes a pollutant, methanogenic microorganisms become emission sources, rumen protozoa and related microbial members become potential intervention targets, and ruminants themselves are easily placed within the governance lens of “emission machines”. Under such a framing, the complex metabolic relations, symbiotic structures, and material pathways inside living systems are compressed into the source of a single emission indicator.

This paper begins from a different framing. Rumen methane is, on the surface, a greenhouse gas emission problem in ruminant production; at a deeper level, it concerns how modern agriculture understands life metabolism, organizes material pathways, accommodates metabolic products, and evaluates whether agricultural modernization is genuinely sustainable. Methane is not an external pollutant that enters agriculture from nowhere. It is a metabolic product formed during anaerobic fermentation in the rumen [4-6]. If it is extracted from the continuous system of animal-microorganism-feed-manure-soil-energy, methane appears only as an emission number to be reduced. If it is returned to the broader relation between life metabolism and agricultural circulation, methane is not merely a pollutant but a metabolic node that has not been sufficiently accommodated.

The ecological value of ruminants lies precisely in their capacity to use rumen microorganisms to decompose grass, straw, and other fibrous plant resources, thereby converting biomass that humans cannot directly digest into milk, meat, manure, and components of ecological circulation [7-8]. In this process, the rumen is not merely a digestive organ but a living reactor co-constituted by the animal body and microbial communities. Methane formation is not an abnormal phenomenon suddenly appearing outside the system; it is a metabolic outlet produced through anaerobic fermentation, hydrogen release, and carbon-flow conversion [4-5]. The key issue, therefore, is not whether this metabolic outlet exists, but whether modern agriculture has designed sufficiently continuous, clear, and effective downstream pathways to accommodate it.

In traditional or relatively low-density agricultural cycles, ruminants, grasslands, crop residues, manure, and soil often maintained closer material relations. Animals consumed plant fiber, transformed it through rumen fermentation into animal products and metabolic residues, and manure returned to the land through composting, field application, or other pathways. Methane still existed in such systems, but it was embedded in a more dispersed, lower-intensity, and more readily accommodated agro-ecological relation. By contrast, under high-density livestock production, dependence on external feed, concentrated manure discharge, insufficient land accommodation, and broken energy pathways, a metabolic outlet once embedded in life circulation becomes amplified into a climate governance pressure [3][9]. The basic question of this paper is therefore not how to eliminate methane, but why methane becomes externalized as a problem under the pathways of modern agriculture.

This reframing has methodological significance. If methane is presupposed as an enemy, governance tends to move toward object removal. If methane is understood as a metabolic node, governance must shift toward pathway diagnosis. The former asks how to inhibit, reduce, or remove a given object; the latter asks where that object is located in the system, why it becomes amplified as a risk, where its downstream pathway breaks, and whether it can re-enter circulation through new accommodation mechanisms. In this sense, this paper argues that enteric methane governance should not stop at numerical reduction at the emission end. It should become an entry point for rethinking animal metabolism, microbial ecology, energy circulation, and the organization of agricultural systems.

1.2 Why methane becomes a governance pressure

Rumen methane is generated through anaerobic fermentation in ruminants, involving plant fiber degradation, microbial cooperation, volatile fatty acid production, hydrogen release, and carbon dioxide reduction. In this process, rumen microorganisms convert fibrous feed into usable energy sources for the animal, while also producing hydrogen, carbon dioxide, and other intermediates. Methanogenic archaea use these intermediates to produce methane, thereby participating, to a certain extent, in the regulation of reductive pressure within the rumen [4-6]. Methane is therefore first a component of animal-microbial symbiotic metabolism, rather than an external pollutant that can be treated apart from the living system.

Modern agricultural structures, however, have transformed the systemic conditions in which this metabolic process occurs. As livestock production becomes increasingly scaled, intensified, and market-oriented, animal numbers are continuously driven upward by production efficiency, market demand, and cost competition. Feed sources are progressively detached from local grasslands and crop residues and incorporated into cross-regional or even global supply chains. Manure treatment and soil return are no longer naturally continuous, and energy recovery systems remain insufficiently embedded in livestock systems [3][9]. The metabolic process inside the animal has not disappeared, but its external accommodation conditions have changed profoundly. Methane is no longer merely a metabolic outlet within a local life process; under conditions of high-density production and pathway rupture, it becomes a large-scale emission pressure.

The deeper contradiction of the rumen methane problem is therefore not that living systems produce methane, but that modern agriculture has not designed clear, continuous, and effective downstream accommodation pathways for this metabolic outlet. Methane is treated as an emission because, after being released from the animal body or the manure system, it is not adequately taken up by energy systems, biological conversion systems, soil circulation systems, or regional resource-management systems. If methane can enter downstream circulation through biogas, microbial conversion, energy use, or other pathways, its systemic identity changes [10-11]. If it can only dissipate into the atmosphere in an unorganized form, it becomes an environmental externality. Methane is thus not merely a molecular problem, but a pathway-organization problem; not merely an emission-volume problem, but a problem of accommodation capacity.

This argument avoids two simplified positions. The first is to treat methane entirely as a natural life process and therefore as something that need not be governed. This ignores the fact that modern agriculture has changed the scale, density, and external accommodation conditions of that life process. Normal metabolism may not constitute severe pressure in low-density, circular systems, but once amplified, concentrated, and externalized through industrialized pathways, it becomes a real environmental governance issue [2-3]. The second simplified position is to treat methane entirely as a pollutant and therefore focus governance on suppressing methanogenesis, manipulating microorganisms, or reducing ruminant numbers. This risks ignoring the physiological position of methane formation and the ecological function of ruminants in agricultural circulation [4][7].

This paper proposes a third interpretation. Methane is neither a natural phenomenon that can be ignored nor a pollutant that should be immediately enemy-framed. It is a metabolic node amplified under specific agricultural systems. Whether it becomes an environmental pressure depends on whether animal metabolism, feed input, stocking density, manure treatment, soil accommodation, and energy recovery form continuous pathways. The issue is not only that methane exists, but that the systemic relations in which methane is located have become imbalanced. The issue is not only how much methane is emitted, but whether the metabolic pathway can be reorganized. Only under this framing can rumen methane governance move from single-indicator management toward agricultural system rebalancing.

1.3 Rebalancing as pathway reorganization, not compromise

Based on this problem framing, the central argument of this paper is that rumen methane governance should not remain confined to a single mitigation indicator. It should proceed from the relations among animal metabolism, microbial ecology, feed structure, manure management, energy recovery, soil circulation, and regional carrying capacity, and should promote the rebalancing of agricultural systems. Rebalancing, as used here, does not mean seeking a moderate compromise between agricultural development and emission reduction. Nor does it dilute the issue into a generic formula of “both production and environmental protection”. Rather, it refers to a methodological shift: redefining the problem object, re-identifying metabolic nodes, redesigning downstream accommodation pathways, and increasing the system’s internal capacity for absorption, conversion, and self-accounting through pathway reorganization.

First, methane is a fact of life metabolism before it is a governance object. Rumen fermentation produces methane because the rumen, as an anaerobic microbial ecosystem, operates through specific modes of hydrogen and carbon-flow conversion [4-5]. Without understanding this physiological position, governance may misrecognize a functional node within a living process as a mere source of risk. This paper does not deny the necessity of methane governance. It argues instead that governance should begin not by negating life processes, but by understanding them. Only after clarifying how a metabolic outlet is formed, why it is amplified, and why it is not accommodated can a more stable governance pathway be designed.

Second, governance should not enemy-frame a microorganism, a metabolic node, or a class of animals. It should determine what function a given element performs under different systemic conditions, why it becomes amplified, and how it can be repositioned. Methanogenic archaea, rumen protozoa, ruminants, and manure are not natural enemies. Under some conditions, they may function as components that support system operation; under other conditions, they may become risk sources because of pathway rupture or scale amplification [6][12]. The problem is not the existence of a node, but whether that node has been placed within a mismatched system pathway. The goal of governance should therefore not be simple object removal, but relation repositioning, pathway accommodation, and externality reduction.

Third, agricultural modernization should not be evaluated only by higher output, lower emissions, or larger scale. It should involve a higher level of systemic organization among animal health, microbial stability, energy accommodation, soil restoration, and regional carrying capacity. Increasing output alone may intensify feed externalization and manure concentration. Reducing emissions alone may impair animal physiological stability or shift problems elsewhere in the system [13]. Expanding scale alone may exceed the carrying capacity of regional land and energy systems [9]. The evaluation of agricultural modernization must therefore ask not only how much is produced and how much is emitted, but whether animals remain healthy, microbial ecosystems remain stable, manure has a downstream pathway, energy can be recovered, soil is compensated, and the regional system retains long-term resilience.

Sustainable agricultural modernization, in this sense, is not modernization as technological expansion. It is modernization in which life-metabolic pathways are properly accommodated, system externalities are internalized as far as possible, and agro-ecological relations are re-accounted. Technology remains important, but it is not the central subject. The central subject is the position of life metabolism, the accommodation pathway of metabolic products, and the capacity of agricultural systems to reduce externalities through reorganization. This paper therefore does not reject mitigation technologies, microbial regulation, feed optimization, or manure valorization. It argues that these technologies must serve system rebalancing rather than dominate the system, sever living relations, or create new pathway mismatches.

1.4 From the rumen micro-ecosystem to the agricultural system

The paper develops its argument through the sequence of problem reframing, modern imbalance, biological foundation, methodological reversal, controversy analysis, pathway reconstruction, system rebalancing, and conceptual conclusion. Its point of departure is neither a macro-policy mandate nor a list of existing mitigation technologies, but the rumen as a micro-scale living system. Through this small but revealing entry point, the paper argues that many governance problems in agricultural modernization do not arise because life processes are wrong in themselves, but because life processes are placed into mismatched industrial pathways. Sustainable governance, therefore, is not the search for an object to remove, but the design of downstream circulation for metabolic products.

The second section examines the imbalance of modern agriculture. It shows that agricultural modernization has improved food supply while also separating what were once more continuous animal-feed-manure-soil cycles into different spaces, industrial chains, and governance segments. Within this separation, methane becomes a visible signal of systemic imbalance. The purpose is not to reject agricultural modernization, but to show that modernization focused only on scale, efficiency, and output, without building accommodation mechanisms, will continue to produce new externalities.

The third section turns to the rumen itself and clarifies methane as a metabolic outlet of anaerobic fermentation. It presents ruminants not as autonomous digesters, but as composite living systems that rely on rumen microbial communities to transform plant fiber. Methane formation is related to hydrogen flow, carbon flow, and anaerobic balance, and therefore cannot be reduced to a functionless waste product. This section establishes a premise for the rest of the paper: governing living systems requires first understanding life processes.

The fourth section introduces the methodological reversal from object removal to pathway diagnosis. Rather than asking only which object produces methane, governance should ask why the node becomes amplified, what pathway it should have entered, and where downstream accommodation has failed. The section examines feed-pathway mismatch, stocking-density mismatch, and manure-pathway mismatch, showing that problems at the emission end often arise from combined imbalances at the input, spatial, and downstream accommodation ends.

The fifth section addresses the controversy over rumen protozoa removal. Rumen protozoa are involved in methane-related processes, bacterial predation, nitrogen cycling, and fermentation patterns, and are therefore often discussed in relation to methane mitigation [12][14-15]. This paper does not directly answer whether they should be removed. Instead, it distinguishes three possibilities: they may be part of an original symbiotic structure; they may be compensatory nodes amplified under abnormal conditions; or they may be regulable members of the system under specific conditions, but not objects to be enemy-framed. This discussion illustrates a broader principle: mature agricultural biotechnology should not rush toward elimination, but should first identify the position of an object in the system and then design an appropriate regulatory pathway.

The sixth section discusses pathway reconstruction: how methane can enter energy, biological conversion, synthetic fuel, and soil-related circulation pathways. Biogas, methane-oxidizing bacteria, microbial protein, synthetic fuels, and high-value methane applications are not introduced as a conventional review of resource utilization. They are used to illustrate the principle that pathway determines identity. Methane is a greenhouse gas when it dissipates in an unorganized form; it can become a fuel in an energy system; it can become a microbial substrate in biological interaction pathways; and it may be connected to resource management and fertility restoration through regional circulation. Valorization is only one form of pathway accommodation, not the final aim. The real issue is how to design the next stage of circulation for a life-metabolic outlet.

The seventh section develops the idea of agricultural system rebalancing through five dimensions: animal, microorganism, soil, energy, and region. Methane governance cannot be evaluated only by emission reduction. It must also ask whether animal health is protected, microbial networks remain stable, manure returns to land, energy is recovered, and stocking scale corresponds to regional carrying capacity. System rebalancing is not anti-technology. It redefines the direction of technology: from reducing a single indicator to reorganizing metabolic pathways, from removing problem nodes to increasing system accommodation capacity, and from short-term efficiency optimization to long-term resilience maintenance.

The final section concludes that the key to sustainable agriculture is not the search for enemies, but the reorganization of relations between life metabolism and modern technology. “No enemy” does not mean denying the need for methane governance or removing constraints on high-emission and high-pollution pathways. It means refusing to enemy-frame functional nodes in living systems before systemic diagnosis has been completed. “Pathways not yet reorganized” means that the real task of sustainable agriculture is to reconnect animals, microorganisms, soil, energy, and regional circulation that have been severed by industrialized pathways. In this way, the rumen methane problem becomes not merely an emission issue, but a theoretical entry point for rebalancing the pathways of agricultural modernization.

2 The Imbalance of Modern Agriculture: When Life Metabolism Is Forced into Industrial Pathways

2.1 From ecological circulation to industrial efficiency

Agricultural modernization has greatly expanded the capacity of human societies to secure food. Through varietal improvement, mechanization, large-scale livestock production, feed industries, chemical fertilizers and pesticides, cold-chain logistics, and global trade systems, limited land can now produce larger quantities of grain, meat, dairy products, and industrial raw materials. Agriculture has thereby gained higher output efficiency and stronger market responsiveness. In the context of population growth, urban expansion, and changing consumption patterns, this increase in efficiency has undeniable historical significance. Without modern agricultural technologies and organizational systems, stable, low-cost, large-scale food supply would be difficult to sustain.

Yet agricultural modernization is not merely a process of output growth and efficiency improvement. It has also transformed the internal material circulation of agricultural systems, moving agriculture away from localized ecological cycles and toward an industrial structure marked by external inputs, high-density production, and global market competition. In earlier agricultural settings, ruminants, grasslands, crop residues, manure, and soil could form relatively continuous material cycles. Animals consumed grass and straw, manure returned to the land, the land produced forage and crops, and animal products entered household consumption or local markets. Within such a structure, animal metabolism was not an isolated physiological process, but an ecological link embedded in land, forage, manure, and farmers' production rhythms.

Modern livestock production often separates this continuous cycle across different spaces, industries, and value-chain segments. Feed production may occur far from the livestock operation and may depend on cross-regional or international trade. Animals are concentrated in high-density facilities to improve managerial efficiency, reduce unit costs, and ensure stable supply. Manure management is separated from soil fertility circulation and becomes an environmental problem requiring specialized treatment. Energy systems are poorly connected to livestock systems, and animal metabolic residues do not necessarily enter energy-recovery pathways. Land absorption capacity no longer naturally determines livestock scale; it is often subordinated to market demand, capital investment, and production-efficiency goals. As a result, land-centered circular agricultural relations are increasingly divided into segmented systems of feed production, livestock production, waste treatment, energy supply, and environmental governance.

This separation produces efficiency, but it also produces rupture. Efficiency appears in the ability to manufacture feed at scale, concentrate animals, stabilize product supply, transport food over long distances, and respond rapidly to market demand. Rupture appears in the detachment of feed sources from local land, the difficulty of returning manure to soil, the release of methane, ammonia, and odor into the air, new pollution pressures on water and soil, and the growing dependence of land on external fertilizers and inputs to maintain yields. Agriculture may appear more modern in terms of output, speed, and scale, while its internal material pathways may become less complete. Excessive specialization and spatial separation can weaken the system's capacity for self-accounting.

The central contradiction of agricultural modernization is therefore no longer only whether output is sufficient, but whether the system can still account for itself. Self-accounting refers to the capacity of a system to reintegrate inputs, transformations, outputs, and residues into a relatively closed cycle, so that animal metabolism, feed sources, manure management, soil accommodation, and energy use remain traceable, returnable, and absorbable. If animal metabolism, feed input, manure output, energy use, and soil accommodation become disconnected, higher production efficiency may concentrate externalities; more visible output may conceal deeper ecological liabilities produced by broken pathways.

This is where modern agriculture must be reconsidered. Industrial pathways are effective at improving the efficiency of particular segments, but they are not necessarily capable of maintaining systemic continuity. Market structures are effective at recognizing product prices, but they do not necessarily record the hidden costs borne by soil, air, water, and animal health. Large-scale production can reduce the unit cost of output, but it may also amplify metabolic processes that were once dispersed and more easily accommodated into regional governance pressures. The methane problem of ruminants is not the only manifestation of this imbalance, but it is an important entry point for observing it. It shows that when life metabolism is forced into industrial pathways, a normal physiological process can be amplified into an environmental problem, a metabolic product that could have entered circulation can be transformed into an externality, and agricultural modernization must move beyond a narrative of efficiency toward a narrative of systemic accommodation.

2.2 Emissions as manifestations of pathway rupture

Within this structure, methane emissions should not be understood as a single animal-physiology problem. They should be understood as the manifestation of ruptured system pathways. Methane production by an individual ruminant is a metabolic fact of anaerobic fermentation in the rumen [4-5]. However, methane pressure at the level of a region, an industrial chain, or an agricultural model cannot be attributed only to the fact that this physiological process occurs inside the animal. The plant material consumed by the animal could, in principle, pass through rumen fermentation, manure transformation, soil return, and energy recovery to form multiple layers of circulation. If these pathways are not organized, residual energy and matter spill outward as gases, pollutants, governance costs, or ecological pressures.

Methane becomes highly visible not only because of its greenhouse effect, but also because it exposes insufficient pathway accommodation in modern agriculture [1-2]. If feed sources remain connected to land systems, livestock scale corresponds to regional carrying capacity, manure returns to soil after appropriate treatment, and biogas or other energy-recovery methods are embedded in livestock systems, methane and related metabolic residues can enter clearer circulation pathways [9-10]. Conversely, when feed is imported from distant sources, animals are highly concentrated, manure accumulates without organization, energy systems are absent, and land cannot absorb residues effectively, methane shifts from a metabolic outlet into an emission pressure. Emissions, in this sense, are not isolated results; they are manifestations of pathway rupture.

This manifestation points in several directions at once. It points first to feed structure. What ruminants eat, how they are fed, the ratio between forage and concentrate, the stability of forage sources, and the dependence of feed production on external land all shape rumen fermentation and methane pathways [17-18]. It points second to rumen microbial ecology. Methanogenic archaea, bacteria, fungi, and protozoa form complex interactions; microbial communities are not merely emission sources, but living networks responding to feed structure, animal condition, and management practices [6][8][12]. It points third to stocking density. The metabolism of individual ruminants may be dispersed and accommodated within ecological circulation, but when animal numbers become highly concentrated and exceed the accommodation capacity of regional land and energy systems, metabolic residues become amplified [3][9]. Finally, it points to manure management, land carrying capacity, and energy use. Methane governance that remains disconnected from these downstream pathways cannot fundamentally alter the pattern of systemic overflow.

Methane is therefore not the only problem in modern agriculture, but it is a clear signal of agricultural imbalance. It reveals relations among the input end, transformation end, output end, and accommodation end. If methane is treated only as a gas produced inside the animal, governance pressure will be concentrated inside the rumen. If methane is treated as the manifestation of system-pathway rupture, one must ask a broader set of questions: where does the feed come from; at what density are animals kept; why does the rumen microbiome operate in its current way; where does manure go; can the soil accommodate it; does the energy system participate; and is regional circulation intact? Only when these questions are raised together can methane governance move beyond point-based mitigation and enter the level of system rebalancing.

If these relations remain broken, reducing a single emission indicator may simply relocate the problem elsewhere in the system. A technical intervention may reduce methane formation while impairing feed intake, digestion, rumination, or microbial stability, thereby transferring environmental pressure into the animal body [13]. Methane production may decrease while manure remains unorganized, ammonia, water pollution, and soil burdens persist, and externalities merely take another form. Feed sources may remain externalized and land carrying capacity may continue to be ignored, so that improved numbers at the emission end conceal enlarged land, energy, and resource consumption upstream. Such governance is not system recovery. It is indicator displacement.

The value of methane governance should therefore not be measured only by reduced emission figures. It should be measured by whether governance pushes the agricultural system to account for itself again. Re-accounting means tracing the problem exposed at the emission end back through the full pathway of feed, animal, microorganisms, manure, soil, and energy; identifying where mismatches occur; locating which pathway lacks accommodation; determining which metabolic residues are spilling outward; distinguishing technologies that merely transfer pressure from mechanisms that genuinely increase internal absorption capacity. Only after this pathway diagnosis can methane governance avoid becoming a single-indicator project and instead serve as an entry point for self-correction in agricultural modernization.

2.3 From mitigation pressure to an entry point for rebalancing

Methane control is now an important issue at the intersection of energy, environment, and agriculture. Methane emissions in agri-food systems arise from multiple sources, including enteric fermentation in ruminants, manure management, rice cultivation, food loss and waste, and changes in land use. Within livestock systems, enteric fermentation and manure management are major components [2-3][16]. This indicates that methane governance is inherently not a point-based task. It is a systemic problem spanning animals, crops, land, energy, and waste management. It occurs inside the animal body and within manure systems; it is linked to feed and livestock management, as well as to land use, energy recovery, and regional circulation.

If methane governance is understood only as external mitigation pressure, the logic of governance is compressed into a single imperative: emissions must fall. Within this frame, ruminants are easily viewed as sources of the problem, rumen microorganisms as intervention targets, manure as a treatment burden, and agricultural systems as passive recipients of climate-governance constraints. Such governance can generate clear targets, but it risks ignoring the internal pathways within agricultural systems that should be reorganized. It may drive local technical improvement without changing deeper structures of feed externalization, livestock concentration, unorganized manure flows, and insufficient soil accommodation.

If methane governance is instead understood as an entry point for agricultural system rebalancing, the questions change. The issue is no longer only how to reduce methane, but whether animal metabolic residues can enter energy systems; whether manure can be transformed into a soil asset through composting, anaerobic digestion, biogas use, and land application; whether methane can be taken up by microorganisms, engineering devices, or regional energy systems; whether feed structure corresponds to the physiological adaptation of ruminants; whether livestock scale matches land carrying capacity and manure absorption capacity; and whether agriculture can shift from a sector that only produces food toward an integrated system that co-produces food, energy, soil restoration, ecological services, and environmental governance [9-11].

Once these questions are raised, methane is no longer merely a passive governance object. It becomes an entry point for reorganizing agricultural pathways. It forces us to see that many "emissions" in agricultural systems are not isolated pollutants, but unaccommodated metabolic products; many "wastes" are not naturally useless materials, but resource nodes that have lost their position because pathways have broken; many "governance pressures" are not merely external policy demands, but signals emitted by the system itself in response to imbalance. The deeper significance of methane governance lies in placing animal metabolism, microbial ecology, manure valorization, soil accommodation, and energy circulation on the same systemic ledger, so that agricultural modernization can no longer explain itself only through output, efficiency, and scale.

From this perspective, the relation between methane governance and agricultural sustainability should not be understood as an opposition between external constraint and internal production. It is better understood as a forcing mechanism. It forces agriculture to reconsider the position of life metabolism; livestock systems to redesign manure and energy pathways; regional agriculture to recalculate land carrying capacity; and technological development to shift from point-based inhibition toward system coordination. Effective governance does not simply add a mitigation burden to agriculture. It uses methane, a visible metabolic signal, to reconnect circular relations severed by industrial pathways.

The basic claim of this section is therefore that the imbalance of modern agriculture does not lie in the failure of agricultural modernization itself. It lies in modernization pathways that overemphasize efficiency, scale, and specialization without simultaneously building mechanisms for metabolic accommodation, resource return, and system self-accounting. Methane matters precisely because it makes this imbalance concrete, visible, and discussable. It shows that the next stage of agricultural modernization should not simply continue increasing unit output or reducing a single indicator. It should improve the capacity of agricultural systems to accommodate, transform, and circulate the products of life metabolism. Only in this sense can methane governance move from mitigation pressure to an entry point for rebalancing, and from passive compliance to a methodological opening for sustainable agricultural modernization.

3 Biological Foundations: Methane Is Not Waste, but a Metabolic Outlet of Anaerobic Rumen Fermentation

3.1 The rumen as a living reactor co-constituted by animals and microorganisms

To reframe the problem of rumen methane, it is necessary to return first to the biological foundation of ruminants themselves. Ruminants can utilize grass, straw, forage, silage, and other fibrous resources not because the animal body alone can efficiently degrade plant fiber, but because the rumen contains a complex and active microbial community. Bacteria, archaea, fungi, and protozoa jointly constitute the rumen fermentation system. They participate in plant cell wall degradation, structural carbohydrate conversion, protein and nitrogen utilization, and fermentation-product formation. Through these processes, ruminants convert plant biomass that humans cannot directly digest or efficiently use into absorbable energy and, further, into agricultural outputs such as milk, meat, fiber, hides, and manure [7-8].

Ruminants are therefore not closed individuals that complete digestion independently. They are composite living systems formed by the animal body and microbial communities. The rumen is not merely a digestive chamber in the ordinary sense, but a dynamic reaction space generated through long-term symbiosis between animals and microorganisms. In this space, the animal provides a stable anaerobic environment, temperature conditions, feed input, and physical mixing; microorganisms perform fiber degradation, fermentation conversion, and energy release. The relation between animal and microorganisms is not external addition, but mutual embedding. Without rumen microorganisms, ruminants could not fully utilize grassland and crop-residue resources; without the physiological environment provided by ruminants, rumen microorganisms could not occupy their present ecological niche in a stable way [7-8].

The rumen should therefore not be reduced to an organ that “emits methane”. It should be understood as a miniature biological reactor within the agricultural ecosystem. Although located inside the animal body, it connects multiple systems outside the body: upstream, it links grasslands, crop residues, feed production, and land use; downstream, it links milk and meat products, manure management, soil fertility, energy recovery, and regional agricultural circulation. Fermentation inside the rumen is not merely an animal physiological event. It is an intermediate process through which agricultural systems determine whether plant material can be transformed, whether energy can be used, and whether residual matter can be accommodated.

In this sense, methane formation is only one outcome of the operation of this living reactor, not its whole function. The core function of the rumen is not to produce methane, but to transform plant fiber into animal-available energy and to maintain digestion and metabolism through a complex microbial network. Methane is a metabolic outlet formed when this anaerobic fermentation system processes carbon flow, hydrogen flow, and reducing pressure [4-5]. If methane is abstracted from the whole rumen system and directly defined as a governance object to be reduced or removed, the system is conceptually severed in advance. The living reactor is simplified into an emission device, and microbial symbiosis is simplified into a pollution source.

This conceptual rupture also reshapes the direction of governance. If the rumen is viewed as an emission source, governance will tend to focus on reducing methane values. If the rumen is viewed as a living reactor, governance must consider feed structure, microbial balance, animal health, fermentation efficiency, and downstream pathways for metabolic products at the same time. The former tends toward point-based intervention; the latter requires methane to be repositioned within a continuous relation among animal, microorganisms, feed, manure, soil, and energy. This article adopts the latter approach because only by first recognizing the integrity of the rumen as a composite living system can normal metabolic processes avoid premature enemy-making, and only then can pathway governance and system rebalancing become possible.

3.2 The physiological position of methane formation: hydrogen flow, carbon flow, and anaerobic balance

During anaerobic fermentation in the rumen, microbial degradation of feed does not produce a single product. After fiber, starch, protein, and other feed components enter the rumen, they are gradually degraded by different microorganisms and converted into volatile fatty acids, hydrogen, carbon dioxide, ammonia, and other fermentation products. Volatile fatty acids are a major energy source for ruminants, while hydrogen and carbon dioxide must be further processed within the anaerobic system. Methanogenic archaea use hydrogen and carbon dioxide to form methane, thereby consuming excess hydrogen and helping maintain the redox balance of rumen fermentation [4-6].

Methane is therefore not functionless waste. It is a metabolic outlet within the carbon-hydrogen conversion relations of the rumen. A metabolic outlet refers to an output pathway formed by a system to release, transfer, or balance specific material and energy pressures while maintaining its own operation. In the rumen, methane formation is closely linked to hydrogen flow, carbon flow, and anaerobic fermentation balance [4-5]. If one sees only methane finally leaving the animal as gas, it appears as a pollutant. If one traces the process by which it forms inside the rumen, it becomes clear that methane participates in material conversion and pressure release within the microbial fermentation network. Its problematic character does not lie in the mere existence of a metabolic outlet, but in whether this outlet is amplified by modern agricultural pathways, whether it lacks accommodation, and whether it becomes a systemic externality.

This point determines the basic position of this article: the greenhouse effect of methane does not justify treating all biological participants in methane formation as enemies. Methanogenic archaea are not natural enemies. Rumen protozoa also cannot be classified as objects to be removed simply because they are associated with methane formation. Every node in a living system may appear as a problem at one scale while performing a function at another. A microorganism may participate in fermentation balance inside the rumen while also being associated with greenhouse-gas pressure at the scale of regional emissions accounting. A metabolic product may function as a hydrogen outlet inside the animal while having climate effects at the atmospheric scale. Function depends on scale; systemic identity depends on pathway.

The real task is therefore not to decide whether a node is simply “good” or “bad,” but to analyze under what conditions it maintains balance and under what conditions it is amplified into risk; in which pathway it functions as a metabolic outlet and after which pathway rupture it becomes an environmental externality. For rumen methane, the key question is not the physiological fact that methane is produced, but why this metabolic outlet overflows in its current scale, form, and pathway within modern agricultural structures. This requires methane formation to be examined within the continuous chain of feed input, rumen microbial ecology, animal condition, stocking density, manure management, and energy accommodation.

Only after the physiological position of methane is clarified can governance direction be properly defined. If methane is understood as a metabolic outlet of rumen fermentation, governance should not be equated with simply cutting off that outlet. It should instead ask whether feed structure can be optimized to reduce unnecessary metabolic pressure, whether microbial regulation can improve fermentation efficiency, whether manure and gas accommodation pathways can reduce unorganized release, and whether part of methane or related organic matter can be converted into energy, fertility, or other circular resources. In other words, governance begins not by negating methane formation, but by understanding it; not by rushing to remove a node, but by determining the node’s position in the system and its downstream pathway.

3.3 Methane as unaccommodated energy, not merely a number to be reduced

Methane has a clear energy property. It can serve as a fuel, and it can also enter higher-value industrial pathways through different processes. The systemic identity of methane is not fixed; it depends on purity, process, transport mode, application scenario, and organizational pathway. When released without organization, methane appears as a greenhouse gas and becomes an emission object in environmental governance. In an energy system, methane can be used for heating, power generation, or partial substitution of fossil fuels. In higher-purity and higher-process contexts, methane may enter chemical, material, or advanced manufacturing pathways. The value and risk of methane are therefore not determined by the molecule alone, but by the pathway, organization, and system into which it is placed.

This has important implications for agricultural methane governance. Methane becomes a problem not because the molecule itself has no value, but because it often escapes agricultural systems in an unorganized form. Methane formed inside the animal is released through eructation, while organic matter in manure systems may continue producing methane under anaerobic conditions. If these gases and organic materials do not enter organized collection, transformation, and utilization pathways, they become environmental externalities. Conversely, if biogas engineering, anaerobic digestion, gas collection, biological conversion, or other technical pathways can accommodate them, methane may shift from environmental burden to energy resource, and from emission pressure to circular node [10-11].

However, resource utilization is not the final position of this article. If the argument stops at "methane can be used," "manure can become energy," or "agricultural waste can create value," it would slide into a conventional resource-valorization narrative and weaken the methodological edge of the article. The central question here is not whether methane can be monetized, nor is it merely to prove that some form of waste has industrial value. The central question is why a metabolic outlet of life has not been accommodated by the system. Why do energy and matter that could have entered circulation become emissions, pollutants, and governance costs within modern agricultural structures? Why has agricultural modernization improved production efficiency without simultaneously improving the accommodation capacity for metabolic residues?

Methane valorization is therefore only one form of pathway accommodation. The underlying methodological shift is from emission governance to pathway governance. Emission governance asks how an indicator can be reduced. Pathway governance asks how a metabolic node can be repositioned, sorted, transformed, and accommodated. Emission governance tends to see methane as a number to be lowered. Pathway governance sees methane as an unorganized flow of energy and matter. The difference is fundamental: the former mainly treats the result, while the latter investigates relations; the former often intervenes at the emission end, while the latter must work through the whole chain of input, transformation, output, and accommodation; the former may produce local improvement, while the latter can support agricultural system rebalancing.

From this perspective, methane is not only a number to be reduced. It is a signal of insufficient systemic accommodation. It shows that energy and matter generated by animal metabolism do not automatically become pollution; they become externalities when downstream pathways are broken, accommodation systems are absent, and regional circulation fails. The key to agricultural methane governance is therefore not only reducing methane formation, but improving the system's capacity to identify, collect, transform, and utilize metabolic residues. Only when methane moves from unorganized release to organized accommodation can agricultural modernization move from producing externalities to internally absorbing them, and from pursuing efficiency alone to building a more complete capacity for circulation.

3.4 Biological positioning as the premise of governing living systems

The central conclusion of this section is that rumen methane is first a fact of life metabolism and only then an object of environmental governance. It forms within the rumen reactor co-constituted by ruminants and microorganisms, participates in hydrogen flow, carbon flow, and redox balance during anaerobic fermentation, and functions as a metabolic outlet within a specific system pathway [4-5][7]. Without understanding this physiological position, governance easily becomes oversimplified: ruminants are treated as emission machines, methanogenic microorganisms as pollution sources, rumen protozoa and other system members as potential enemies, and methane formation as a single object to be suppressed.

The risk of such simplified governance is that it may exchange system disturbance for indicator improvement. If governance focuses only on emission values while ignoring animal health, microbial balance, feed adaptation, and downstream accommodation pathways, it may reduce methane locally while damaging rumen stability, transferring metabolic pressure, or pushing the problem into manure, water, soil, and the animal body itself [13]. For living systems, governance cannot ask only whether an indicator has declined. It must also ask whether the system has become more stable, whether the animal is healthier, whether microbial ecology is more coordinated, whether metabolic residues are better accommodated, and whether externalities are genuinely reduced. Otherwise, governance merely relocates the problem.

Truly sustainable governance should begin with recognizing life processes rather than negating them. It should begin with locating metabolic nodes rather than clearing governance objects. Rumen methane matters because it reveals a fact often overlooked in agricultural systems: many objects called “emissions” or “wastes” originally have physiological, ecological, or material-circulation positions. They become problems not because they are inherently harmful, but because their pathways are severed, their downstream accommodation is absent, and their system relations are imbalanced. Understanding this is the prerequisite for moving from a single mitigation logic to a pathway-governance logic.

This section therefore prepares the methodological reversal developed in the next section. If methane is not simple waste but a metabolic outlet of anaerobic rumen fermentation; if the rumen is not an emission organ but a living reactor co-constituted by animals and microorganisms; and if the risk and value of methane depend on the pathway into which it enters, then the core of governance should not remain with the question of which object produces methane. It should move to the question of which pathway is mismatched. The problem lies not in the existence of nodes, but in pathway mismatch. Governance should not begin with object removal, but with pathway diagnosis.

4 Methodological Reversal: The Problem Lies Not in the Existence of Nodes, but in Pathway Mismatch

4.1 From object removal to pathway diagnosis

In addressing enteric methane emissions, conventional governance approaches often begin by identifying the objects that produce methane. Methanogenic archaea are readily treated as core regulatory targets because they directly participate in methane formation. Rumen fermentation is also placed within the scope of technical intervention because it determines hydrogen flow, carbon flow, and volatile fatty acid production. Feed additives, rumen modifiers, microbial inhibition strategies, and protozoa-removal approaches all reflect this object-oriented and node-oriented mode of governance [4][18-19]. Such approaches are not without value. Under specific conditions, regulating microbial activity, optimizing feed formulation, redirecting fermentation, or reducing the activity of certain methane-associated nodes may generate local mitigation effects and may even improve aspects of energy-use efficiency.

However, if governance remains at the level of objects, complex living relations are easily compressed into a logic of object removal. Object removal does not only mean physically eliminating a biological group. It also includes the conceptual act of defining a node in advance as the source of the problem, and then designing suppression, weakening, replacement, or removal strategies around that node. The risk is that, once the question is framed as "which object produces methane," the analysis may neglect why that object becomes amplified under particular system conditions, what function it originally performs in life metabolism, and how it is related to feed structure, animal condition, stocking density, manure pathway, and regional carrying capacity. Governance then appears more precise while becoming narrower; the technology appears more direct while obscuring the deeper systemic lesion.

The methodological reversal proposed here is to move from object removal to pathway diagnosis. Pathway diagnosis means that before deciding whether a node should be intervened in, one must first ask whether the pathway in which the node is embedded has become mismatched. The question should not only be "which node produces methane," but also: why is this node amplified here? Into which cycle was it originally supposed to be integrated? Which pathway has broken down and turned it from a functional node into a source of externality? If this node is directly suppressed or removed, will the system return to balance, or will new compensation and overflow emerge elsewhere? These questions expand the object of governance from a single point to a pathway, and shift the target of governance from indicator reduction to relational reorganization.

Once the problem moves from "which object is responsible" to "how the pathway is mismatched," the logic of governance also changes. The aim is no longer to find an enemy, but to reorganize relations. It is no longer to isolate and remove a node, but to restore the system's capacity for accommodation. Methane is no longer treated as a single emission outcome, but as the visible expression of broken relations among feed input, rumen fermentation, animal metabolism, manure management, energy use, and soil return. Enteric methane governance therefore ceases to be merely a technical issue of livestock mitigation. It becomes a comprehensive question concerning whether agricultural modernization has complete pathways, whether metabolic products are accommodated, and whether systemic externalities are internalized.

This methodological reversal is fundamental because many nodes in living systems do not exist naturally as "problems." They are often functional nodes first, and become risk nodes only under particular environmental, scalar, pathway, and accommodation conditions. This is true of methanogenesis. It is true of manure. It may also be true of rumen protozoa. If governance precedes diagnosis, technology may prematurely make enemies of system members. If diagnosis precedes governance, technology can serve system recovery. The claim that "the problem lies not in the existence of nodes, but in pathway mismatch" is intended to prevent agricultural governance from falling into a repetitive cycle: identify a problematic object, suppress it, and then encounter a new problematic object. Instead, governance must move toward a higher-level form of systemic accounting.

4.2 Feed-pathway mismatch: emission-end problems often originate in input structures

Rumen methane is not generated in the animal body out of nothing. It is closely linked to the structure of the feed consumed by ruminants. Forage proportion, digestibility, concentrate-to-forage ratio, forage type, feed processing method, additive use, feeding rhythm, and feed origin all shape the rumen microbial community and the direction of fermentation. Once different feeds enter the rumen, they alter the type of fermentable substrate, the proportion of volatile fatty acids produced, the level of hydrogen release, and microbial competition. These changes then influence methane formation. Methane appears at the emission end, but its conditions are often shaped much earlier at the feed-input end [17-19].

If feed structure matches the physiological adaptation of ruminants, the rumen microbial ecology is more likely to maintain relatively stable fermentation rhythms. If feed structure departs too far from the animal's digestive basis-for example, through insufficient forage quality, excessive concentrate ratio, abrupt feeding rhythms, or feed sources disconnected from local land systems-the rumen may enter a state of metabolic pressure. Such pressure may not appear only as a change in methane. It may also appear as pH fluctuation, altered feeding behavior, reduced digestive efficiency, microbial-network restructuring, and increased animal-health risk. Methane formation is therefore not an isolated gas-production event. It is the result of feed input, microbial response, and animal metabolism acting together [17-18].

Emission-end problems are thus often the visible expression of feed-input structures. If we do not ask what animals eat, where feed comes from, whether feed production damages land, and whether feeding practices align with ruminant physiological rhythms, we cannot understand why methane appears in its current form. Placing the entire burden of governance inside the rumen may obscure how feed structure, cropping systems, and land use shape methane pathways upstream. For example, if a livestock system relies heavily on externally produced, high-input feed while neglecting local forage supply, forage quality, and land-carrying relations, rumen-end mitigation technologies may merely patch an upstream pathway mismatch at its terminal point.

True pathway diagnosis must begin at the input end, not only at the emission end. Input diagnosis does not merely mean optimizing ration formulation. It means placing feed back into the agricultural system: does feed come from local land? Is forage production coordinated with soil restoration? Can crop residues enter ruminant-use pathways through appropriate processing? Does feed production depend excessively on fertilizers, pesticides, energy, and long-distance transport? Does feeding practice serve animal health rather than simply short-term weight gain or milk yield? These questions determine whether methane governance is only a technical adjustment inside the rumen or a structural optimization of the agricultural input system.

From this perspective, feed-pathway mismatch reveals a core problem of modern agriculture. Many emission pressures do not suddenly appear at the emission end; they accumulate through the input, production, and organization ends. When the feed system is detached from the land system, animal metabolism is detached from regional circulation. Once animal metabolism is detached from regional circulation, manure and methane more easily become externalities. Enteric methane governance cannot therefore remain confined to the animal body. It must return to the continuous relation among feed, land, and animal. Only when feed pathways are reorganized in ways that align animal physiology, land carrying capacity, and regional circulation can emission-end governance gain a stable systemic foundation.

4.3 Stocking-density mismatch: how normal metabolism becomes environmental burden

Methane production by individual ruminants is a normal biological phenomenon of anaerobic rumen fermentation. The problem is not the fact that “cattle produce methane,” but how modern agriculture organizes the number, spatial distribution, feed supply, and metabolic outputs of cattle, sheep, and other ruminants. When herd size is matched with regional land, forage, manure assimilation, and energy accommodation, animal metabolism can more easily be integrated into local circulation. But when stocking density rises sharply, animals are concentrated in limited spaces, feed is imported from outside, and manure accumulates without timely return to land or resource recovery, a local flux within a life cycle becomes amplified into an environmental governance pressure [3][9].

The issue in modern agriculture is therefore not simply that animals emit. It is the scale, density, and spatial organization through which animals are incorporated into production systems. The same number of ruminants may produce very different environmental consequences under different land-carrying conditions, feed sources, manure-management capacities, and energy-system configurations. If animals are distributed across grasslands, croplands, and regional circulation systems, their metabolic outputs may more easily return to material cycles through manure, soil, and vegetation. If animals are highly concentrated in feedlots or farms while nearby land cannot accommodate manure and energy systems cannot recover residual organic energy, methane, ammonia, odor, water pollution, and public governance costs become concentrated externalities.

Governance must therefore look beyond the animal body and return to spatial organization and production scale. One of the central problems of modern livestock systems is that market demand and short-term profit can continually drive herd expansion, while regional carrying capacity does not necessarily grow with it. Farms can expand, animal numbers can increase, feed can be transported over long distances, and products can enter larger markets. Yet manure-application radius, soil-absorption capacity, water conditions, air-environmental capacity, and energy-recovery infrastructure all have regional limits. If these accommodation conditions are not built at the same time, the larger the production scale, the more obvious the pathway mismatch, and the more likely normal metabolism is amplified into environmental burden.

When livestock scale exceeds the carrying capacity of regional land, energy systems, and manure management systems, methane problems are inevitably magnified. Technical measures can relieve local pressure, but they cannot replace regional carrying-capacity judgment. Feed additives or rumen-regulation technologies, for instance, may reduce methane emissions per animal. But if total animal numbers continue to rise, manure remains disorganized, land cannot absorb nutrient flows, and energy recovery remains insufficient, aggregate pressure and systemic externalities may continue to increase. Improvements in individual efficiency do not necessarily reduce system burden; they may even be offset by scale expansion.

Agricultural system rebalancing requires stocking density, land assimilation, energy recovery, and ecological capacity to be recalculated within the same system account. The number of ruminants suitable for a region should not be determined only by market demand, short-term profit, or facility capacity. It should also be determined by forage supply, manure return, soil organic-matter demand, water conditions, gas-emission accommodation, energy-recovery capacity, and ecological-environmental capacity [9]. Only when animal numbers are aligned with regional accommodation capacity can methane governance move beyond end-point mitigation and enter production organization itself. Stocking-density mismatch is therefore not only an environmental issue. It is also an issue of agricultural modernization: a truly advanced livestock system is not one that indefinitely increases density and output, but one that organizes animal metabolism, land carrying capacity, and regional circulation at a higher level.

4.4 Manure-pathway mismatch: from fertility return to unorganized release

Animal metabolism does not end with methane emissions. After ruminants and other livestock consume feed and complete digestion and absorption, they produce feces, urine, and other metabolic residues. If these residues are processed through composting, anaerobic digestion, biogas use, digestate return, and soil assimilation, they can become sources of energy, fertilizer, and soil organic matter. If they are stored in the open for long periods, discharged without treatment, or produced beyond the carrying capacity of nearby land, they become sources of methane, odor, water pollution, pathogen risk, and public governance costs. The same manure therefore becomes entirely different system variables under different pathways [10].

Manure is not a natural pollutant. It is a metabolic residue whose identity is determined by pathway. Its character is not decided by the material alone, but by whether it is integrated into subsequent cycles. Manure contains organic matter, nitrogen, phosphorus, potassium, and other nutrients, and it can also continue releasing methane and other gases under anaerobic conditions. If these nutrients return to land after proper treatment, they can supplement soil fertility, reduce part of the dependence on external fertilizers, and reconnect animal metabolism with plant production. If the organic matter enters a biogas system, it can be converted into energy and reduce unorganized emissions. If all such pathways are broken, manure shifts from fertility resource to pollution burden [10][20].

The difference between fertility return and unorganized release lies not in the substance itself, but in system organization. When cattle manure, pig manure, and other livestock wastes are connected to composting, biogas, syngas, sustainable fuels, or carbon-asset mechanisms, they shift from pollution sources to energy and value sources. When they cannot return to land, cannot enter energy systems, and cannot be accommodated by regional circulation, they become environmental burdens. This does not mean that, because manure can be valorized, livestock scale should be expanded without limit. On the contrary, it means that resource-recovery pathways must serve system rebalancing rather than becoming a justification for another round of scale expansion. The goal of manure-pathway reconstruction is to reduce unorganized overflow of metabolic residues, not to create commercial outlets for ever larger quantities of residues.

This is fully consistent with the central argument of this article: the problem lies not in the material itself, but in whether the pathway has been reorganized. “Waste” is often a resource node that has not yet been repositioned. “Pollutant” is often a metabolic residue that has not been accommodated by an appropriate system. “Governance cost” is often the concentrated visibility of upstream pathway rupture in downstream public systems. Manure governance should therefore not be understood merely as end-of-pipe treatment or environmental sanitation engineering. It must be redesigned within the continuous relation among animal metabolism, soil fertility, energy recovery, and regional circulation.

Manure-pathway mismatch also shows why methane governance must move beyond the animal body. Even if rumen regulation reduces part of enteric methane, agricultural systems may still release methane and other environmental pressures elsewhere if manure remains disorganized. Conversely, if manure enters organized anaerobic digestion, biogas recovery, fertilizer use, and soil-restoration pathways, methane may still exist as a metabolic product, but it can become part of internal system circulation. The governance focus must therefore shift from reducing a single gas to organizing the pathways of metabolic residues. Only then can externalities be genuinely reduced rather than transferred among different links of the system.

4.5 Reorganizing broken pathways as the core task of agricultural modernization

This section has developed a methodological reversal. Its central conclusion is that methane governance cannot remain within the linear logic of “detect emissions-reduce emissions.” Rumen methane is not an isolated emission outcome. It is the visible expression of interacting feed pathways, rumen pathways, livestock-organization pathways, manure pathways, energy pathways, and soil pathways. If these pathways are broken apart, methane appears as emission pressure. If they can be reorganized, methane and related metabolic residues may enter energy, fertility, biological conversion, and regional circulation. The key to governance is not to make a node cleaner in isolation, but to make broken pathways more continuous, more accommodative, and less prone to externalization.

The shift from object removal to pathway diagnosis is the most important methodological move in this article. Object removal asks who caused the problem. Pathway diagnosis asks what relations make the problem appear. Object removal tends to push a microorganism, a metabolic product, or a class of animals into the position of governance object. Pathway diagnosis requires that object to be placed back into the system so that its functional position, amplification conditions, and accommodation pathway can be analyzed. The former easily produces enemy-thinking; the latter emphasizes relational repositioning. The former may generate local indicator improvement; the latter is more likely to support system recovery.

Feed-pathway mismatch shows that emission-end problems often originate in input structures. If feed origin, feeding rhythm, and ruminant physiological needs do not align, rumen metabolism may come under pressure and methane pathways may change accordingly. Stocking-density mismatch shows that normal metabolism often becomes environmental burden because animal numbers, spatial organization, and regional carrying capacity are misaligned. Manure-pathway mismatch shows that metabolic residues become pollutants when energy systems, soil systems, and regional circulation systems fail to accommodate them. Together, these mismatches demonstrate that methane governance must move from the emission end back to the pathway chain, and from point intervention back to system organization.

The real challenge of agricultural modernization is therefore not merely to increase output, reduce emissions per unit, or expand technical application. It is to rebuild the pathway-accommodation capacity of agricultural systems. If modern agriculture pursues efficiency without accommodating the metabolic residues behind that efficiency, it will continue to generate externalities. If it pursues mitigation indicators without repairing the broken relations among feed, animals, manure, soil, and energy, it will only move problems from one site to another. Truly sustainable modernization must place life metabolism within complete pathways, place residues within subsequent cycles, place local indicators within systemic accounts, and place technological intervention within ecological carrying capacity.

This methodological foundation leads directly to the next section on the rumen-protozoa controversy. If the problem lies not in the existence of nodes, but in pathway mismatch, then a concrete microbial node such as rumen protozoa cannot be approached only through the question of whether it should be removed. It must be analyzed as a possible original symbiotic structure, a compensatory node amplified under abnormal conditions, or a regulatable system member that should not be made into an enemy. Only when microbial intervention is discussed on the basis of pathway diagnosis can agricultural biotechnology move from point removal toward system recovery.

5 The Rumen-Protozoa Controversy: Enemy, Compensatory Node, or Symbiotic Structure?

5.1 Why the controversy matters: a microbial question that exposes a governance logic

Rumen protozoa occupy a contested position in discussions of enteric methane mitigation. On the one hand, as an important component of rumen protozoal communities, they participate in rumen fermentation, bacterial predation, feed-particle degradation, nitrogen cycling, and the regulation of microbial-community structure. On the other hand, their activities may also be indirectly associated with methane formation by affecting hydrogen flow, bacterial populations, and symbiotic relations with methanogenic archaea. For this reason, reducing or removing rumen protozoa is sometimes considered as one possible strategy for regulating rumen ecology, redirecting fermentation, and lowering methane-production potential [12][14][21].

Yet the significance of the rumen-protozoa controversy does not lie only in whether protozoa should be removed. If the discussion remains confined to removal or retention, a complex microecological relation is reduced to a binary choice: preserve them or eliminate them; support them or oppose them; treat them as beneficial members or as obstacles to mitigation. This mode of discussion exposes a common habit in governing living systems. Once a node becomes associated with a problematic indicator, it is readily defined as an intervention target. Once a living member is linked to emissions, pollution, or efficiency loss, it is pushed further toward the position of something to be weakened, replaced, or removed. A relational problem is thereby converted into an object problem, and system diagnosis is simplified into node treatment.

The real value of the rumen-protozoa controversy is that it forces a distinction among three possibilities. First, rumen protozoa may be an original symbiotic structure formed through the long coevolution of ruminants and their microbial partners, helping maintain rumen microecological stability and fermentation rhythms. If so, simple removal may disturb existing metabolic balance. Second, rumen protozoa may become a compensatory node amplified under abnormal feed structures, high-density production pressure, or altered rumen environments. In this case, their association with methane formation may not mean that they are the root cause. It may instead indicate that they are one visible expression of system imbalance. Third, rumen protozoa may be system members that can be regulated under specific conditions, but should not be made into enemies in advance. They are not necessarily beyond intervention, but neither should they be predefined as objects that must be eliminated.

These three possibilities correspond to three different governance logics. If rumen protozoa are an original symbiotic structure, governance must first protect overall stability and avoid exchanging systemic disturbance for improvement in a single indicator. If they are compensatory nodes amplified under abnormal conditions, governance cannot stop at the protozoa themselves; it must return to feed structure, rumen environment, and production pressure. If they are regulatable variables, intervention should proceed only with clear boundaries, objectives, and system-level assessment. The real question raised by the protozoa controversy is therefore not whether protozoa are “good” or “bad,” but whether governance has the capacity to determine the position of a node within a living system.

Without such distinctions, any discussion of “removal” compresses a relational question into object management. Rumen protozoa are not isolated microbial objects. They are relational nodes embedded in rumen ecology, feed input, animal physiology, nitrogen cycling, carbon-hydrogen flows, and methane pathways. Their functions and effects cannot be judged apart from specific system conditions. This article treats the controversy as a methodological test case. The aim is not to endorse a particular technical scheme directly, but to show that mature agricultural biotechnology is not defined by how quickly it identifies removable objects. It is defined by whether it can identify the relational structure, pathway conditions, and systemic consequences behind an object.

5.2 If protozoa are an original symbiotic structure, removal may disturb metabolic balance

If rumen protozoa are part of an original symbiotic structure formed through the long evolution of ruminants, they should not be understood too quickly as mere obstacles to methane mitigation. The rumen is not a simple digestive chamber. It is a composite living reactor co-formed by the animal and its microbial community. Bacteria, archaea, fungi, and protozoa interact within this space and jointly participate in plant-fiber degradation, starch utilization, protein breakdown, nitrogen cycling, and fermentation-product generation. As important members of this system, rumen protozoa may contribute to overall rumen function by preying on bacteria, engulfing starch particles, regulating fermentation speed, influencing nitrogen flow, and stabilizing parts of the microecological network [8][12].

Under such conditions, removing protozoa may alter methane pathways, but it may also change rumen ecology, nutrient-use efficiency, and the animal's overall metabolic state. No microbial group performs only a single function. A group may appear unfavorable with respect to one indicator, while performing buffering, regulatory, or stabilizing roles at another level. If protozoa are treated as objects of removal simply because they are associated with methane formation, their roles in feed-particle processing, bacterial-community regulation, and fermentation rhythm may be overlooked. A reduction in a mitigation indicator does not necessarily mean that system status has improved. A decline in one microbial group does not necessarily mean healthier animal metabolism [12][15].

For an original symbiotic structure, removal cannot be justified on the basis of a single emission indicator alone. Balance in living systems often emerges from dynamic interactions among multiple biological groups, not from the absolute benefit or harm of one member. Point removal may reduce one risk while opening another. It may change one gas-production pathway while affecting nutrient absorption, microecological stability, animal health, or other metabolic outlets. Especially in a symbiotic digestive system such as the rumen, any intervention in major microbial relations should be evaluated within the overall fermentation network and the animal's physiological condition, rather than only through a single emission outcome.

A more cautious approach is not to ask first whether protozoa can be eliminated, but to ask under what conditions they help maintain system balance. Under which feed structures do they help stabilize fermentation rhythm? With which fiber-degrading bacteria, starch-utilizing bacteria, methanogenic archaea, and fungi do they interact? How do they affect rumen pH, nitrogen cycling, and volatile fatty acid profiles? Do changes in protozoal abundance reflect upstream feed structure, production pressure, or altered rumen conditions? Only when such questions are addressed can removal, suppression, or regulation move from crude intervention toward precise judgment.

The methodological point is that an original symbiotic structure cannot be arbitrarily made into an enemy. "Original" does not mean forever beyond intervention. It means that the node must first be understood as part of a system relation. If a living node has long existed within the ruminant digestive system and forms a stable network with other microorganisms, feed substrates, and animal metabolism, governance must proceed with caution. Technical maturity does not lie in the speed with which a node can be cut out of a system. It lies in the capacity to determine that node's functional boundary, risk conditions, and regulatory range, and to intervene only within a framework that protects overall stability.

5.3 If protozoa are compensatory nodes under abnormal conditions, removal does not equal recovery

A second possibility is that rumen protozoa are not merely stable symbiotic members under all conditions, but compensatory nodes amplified in abnormal environments. A compensatory node is a member that assumes greater functional burden, abnormal abundance, abnormal activity, or abnormal influence when a system is under pressure, deviates from its previous balance, or enters a mismatched pathway. Such a node may appear to be the focal problem, but it is not necessarily the root cause. It may instead be the visible site where system imbalance is expressed.

In ruminant production, unreasonable feed structures, high-density production pressure, imbalanced forage-to-concentrate ratios, rumen pH fluctuations, altered feeding rhythms, and long-term external interventions can all change the rumen microecological environment. If these conditions alter protozoal abundance, function, or interactions, protozoa may be pushed from their original symbiotic position into a compensatory role. Their association with methane formation, hydrogen transfer, or bacterial-community shifts may indicate that the rumen system is adapting to external pressure in a particular way, rather than proving that protozoa themselves are the entire problem[12][21].

Under such conditions, removing or suppressing protozoa may bring local improvement, but it does not mean that the system has returned to normal. The real problem may still lie in feed, environment, pressure, and management pathways. If the feed structure remains misaligned with the animal’s physiological needs, stocking density still exceeds regional carrying capacity, feeding rhythms remain unstable, manure pathways remain disorganized, and animals remain under high metabolic pressure, removing a compensatory node only changes the form in which imbalance appears. The system may continue to search for new compensatory pathways, and risks may reappear in another microbial group, another metabolic outlet, or another physiological indicator.

Governance of living systems must therefore go beyond managing compensatory expressions. It must ask why compensation occurs. If abnormal protozoal changes result from feed-structure shifts, the governance focus should return to the feed pathway. If protozoal functional shifts are related to rumen pH, feeding rhythm, concentrate-to-forage ratio, and buffering mechanisms must be examined. If protozoal changes are related to animal stress under high-density production, stocking density, animal welfare, and regional carrying capacity must be discussed. If protozoal dynamics are associated with reinforced methane pathways, methanogenic archaea, hydrogen flow, manure accommodation, and energy recovery must also be examined. Only then can the protozoa controversy be transformed from “removing a microorganism” into “diagnosing a set of system conditions.”

This judgment has broader implications for agricultural modernization. Many modern agricultural governance schemes mistake compensatory nodes for root causes. When a disease increases, a stronger chemical control is immediately sought. When an emission rises, a suppressible object is sought. When a microorganism becomes associated with a risk indicator, it is immediately defined as a governance target. Yet if these phenomena arise from pathway mismatch, excessive density, input imbalance, or broken accommodation, point governance will continually chase compensatory expressions without restoring system conditions. The protozoa controversy reminds us that compensatory nodes may indeed require governance, but before governing them, we must understand why the system has pushed them to the foreground.

5.4 If removal is locally effective, it must still serve system recovery

To argue against making rumen protozoa into enemies is not to reject technical intervention. Under certain conditions, regulating rumen protozoa, altering microbial structure, optimizing fermentation pathways, or redirecting hydrogen flow may help reduce methane emissions, improve energy use, or adjust fermentation profiles. Especially when feed conditions, animal status, production goals, and environmental constraints are clearly specified, limited microecological regulation may become part of system governance [14-15][22]. This article therefore does not reject technology. It redefines the position of technology.

The key point is that removal or regulation must be subordinated to system recovery. It cannot replace system recovery itself. System recovery does not mean returning to a static original state. It means rebuilding relations among animal health, rumen stability, feed structure, manure accommodation, energy use, and soil circulation in ways that reduce externality, increase accommodation capacity, and enhance resilience. If microbial regulation serves this goal, it can be used cautiously as a tool. If it only reduces one emission indicator without changing upstream feed mismatch, stocking-density pressure, or manure-pathway rupture, then it becomes a local indicator project rather than sustainable governance.

More precisely, removal or regulation may be a tool, but it must not become a worldview. As a tool, it must answer system-level questions. Does it protect feed intake and rumination behavior? Does it maintain stable rumen fermentation? Does it improve nutrient use without creating new metabolic pressure? Is it coordinated with feed-structure adjustment, manure management, and energy accommodation? Does it reduce systemic externality rather than transfer pressure into the animal body or downstream governance systems? Only when these questions are addressed does microbial intervention acquire systemic significance. Otherwise, it may be technically effective but systemically misdirected.

If the tool begins to dominate the system and reduces life processes to indicator objects, it departs from the direction of sustainable agriculture. Once technology is pulled by a single indicator, it easily develops a governance habit: where there is emission, there must be suppression; whichever object is associated with the indicator must be removed. Such technology is not necessarily more advanced. It may improve a short-term measurable index while weakening system resilience. It may reduce one gas pathway while disturbing animal physiology. It may lower unit emissions while amplifying feed dependence, manure pressure, or regional externalities. What sustainable agriculture needs is not stronger removal capacity, but a higher capacity for relational identification and pathway organization.

Mature biotechnology is therefore not measured by how many objects it can remove, but by whether it understands relations, reduces externalities, restores accommodation pathways, and protects system stability. Whether rumen protozoa should be regulated cannot be decided outside context. Whether regulation is reasonable cannot be decided by methane indicators alone. It must serve the higher-level goals of animal health, microecological stability, feed-pathway optimization, manure accommodation, and regional rebalancing. Only in this way can agricultural biotechnology avoid becoming a new source of systemic disturbance and instead become part of agricultural system rebalancing.

5.5 No natural enemies: only relations requiring repositioning

This section has used the rumen-protozoa controversy to clarify the methodological position of this article. Nodes in living systems cannot be simply classified as “good” or “bad.” Nor should they be predefined as enemies merely because they are associated with a problematic indicator. Whether rumen protozoa are original symbiotic structures, compensatory nodes amplified under abnormal conditions, or system variables that can be regulated under specific circumstances depends on feed structure, rumen environment, animal status, production mode, and regional accommodation conditions. To discuss removal apart from these conditions is to reduce a complex system problem to object treatment [12][21].

If rumen protozoa are original symbiotic structures, governance should first understand their functional position in rumen ecology and avoid disturbing overall metabolic balance for the sake of a single mitigation indicator. If they are compensatory nodes amplified under abnormal conditions, governance should investigate the upstream conditions that generate compensation rather than merely treating its expression. If they do have regulatory value under local conditions, that regulation must still serve system recovery and cannot replace the reconstruction of feed pathways, stocking density, manure accommodation, and regional circulation. The rumen-protozoa controversy therefore becomes a methodological test: are we governing a living system, or merely removing objects associated with indicators?

Mature agricultural biotechnology does not rush to eliminate an object. It determines the object’s position in the system and designs a more stable regulatory pathway accordingly. It moves from enemy-thinking to relational thinking, from point suppression to network regulation, and from end-point indicator improvement to system-pathway recovery. This is not a weaker or more compromising form of technology. It is a higher level of precision: knowing when to intervene, when to preserve, when to return to upstream conditions, and when to design downstream accommodation pathways.

The rumen-protozoa controversy is therefore not only a microbial issue. It is a concentrated expression of the methodological argument of this article. “No natural enemies” does not mean that agricultural systems contain no risk nodes, nor does it mean that governance requires no intervention. It means that every node must first be understood within its relational network. “Relations requiring repositioning” means that the real object of governance is not an isolated living member, but the pathway conditions, system environments, and accommodation failures that amplify that member into a risk. Only in this sense can enteric methane governance move from object removal to pathway governance, and from microbial controversy to agricultural system rebalancing.

6 Pathway Reconstruction: Letting Methane Enter the Next Cycle

6.1 From reducing methane to accommodating methane

If the previous sections have shown that rumen methane is not a pollutant that can be treated apart from living systems, but a metabolic outlet formed during anaerobic fermentation in ruminants, the next question is whether this outlet has a subsequent accommodation pathway after it leaves the rumen or manure system. Methane becomes an environmental pressure not simply because it is generated, but because in modern agricultural systems it often escapes in an unorganized, unaccommodated, and untransformed form. When a metabolic node is embedded in a complete systemic cycle, it may become part of energy flow, material flow, and ecological circulation. When it is cut off at the emission end, it appears as externality, pollutant, and governance cost.

Methane governance should therefore not remain limited to the surface objective of “reducing methane.” It should move toward the more fundamental task of accommodating methane. Accommodation here does not mean simply repackaging methane as a “usable resource,” nor does it mean using the language of resource utilization to downplay its greenhouse effect and environmental risk. It means placing methane back into a pathway relation: where it comes from, why it escapes at this point, which cycle it could have entered, and which mechanisms of collection, transformation, use, and return are missing from the current agricultural system. Only when these questions are incorporated into the same analytical framework does methane cease to be only an emission number. It becomes a node through which the continuity of agricultural pathways, the accommodation of metabolic products, and the internalization of systemic externalities can be assessed.

In this sense, accommodating methane has at least three implications. First, it means converting unorganized escape into organized collection, so that methane that would otherwise enter the atmosphere directly can enter technical pathways that are manageable, measurable, and usable. Second, it means converting environmental burden into energy input, so that the energy contained in manure and organic residues does not remain trapped in the identity of pollution but can enter biogas, heating, electricity, biomethane, or other energy systems. Third, it means converting local pollution pressure into a regional circular resource, reconnecting animal metabolism, manure management, energy recovery, soil fertility, and agricultural production. Methane governance then becomes not only a reduction of an emission indicator, but part of the reconstruction of agricultural pathways.

This section discusses biogas pathways, methane-oxidizing microorganisms and microbial-protein pathways, synthetic-fuel pathways, and high-value methane pathways. These discussions are not intended to turn the article into a conventional review of agricultural waste valorization. They serve a more central methodological claim: pathway determines identity. The same methane functions as a greenhouse gas in an unorganized emission pathway, as a fuel in a biogas-energy pathway, as a substrate for another microbial process in a biological-interaction pathway, and potentially as a high-value industrial gas in a high-purity gas pathway. Risk, value, and liability are not determined by the substance alone. They are co-determined by the pathway in which it is placed, the mode through which it is accommodated, and the degree to which the system is organized.

The key governance question is therefore not only “how much less is emitted,” but also “who accommodates the emitted metabolic product, where it goes, what value it is transformed into, and whether systemic leakage is reduced.” If a technology lowers emissions at one point while transferring pressure to animal health, manure treatment, land pollution, or regional ecological capacity, it remains a local governance measure. By contrast, if a pathway can return previously leaking energy and matter to energy systems, soil systems, biological manufacturing, or regional circulation without undermining animal metabolic stability, it is more than a resource-use technology. It becomes an accommodation mechanism for agricultural system rebalancing.

6.2 The biogas pathway: bringing manure into the energy system

Anaerobic digestion and biogas engineering are among the most direct and easily understood pathways for methane accommodation. Livestock manure contains large amounts of organic matter. When it is piled up in an unorganized manner or insufficiently treated, it may generate methane, odor, water pollution, and sanitation risks. When processed through organized anaerobic digestion systems, however, its organic matter can be converted into biogas and further used for electricity generation, heating, cooking fuel, biomethane, or other regional energy purposes. Manure then ceases to be merely a pollution burden left behind after animal production. It becomes an organic feedstock within the energy system [10][20].

The significance of this transformation is not only pollution treatment. It changes the position of animal metabolic residues within the agricultural system. Conventional treatment logic often places manure at the tail end of livestock production: animals are raised first, products are obtained, and the remaining waste is then handled by producers or environmental-governance systems. The biogas pathway moves this tail-end problem upstream into system design. Animal metabolic residues should be considered from the beginning as part of an integrated pathway of energy circulation, fertility return, and environmental governance. Livestock production is no longer only an emission end; it can also become part of regional energy circulation. Manure is no longer only a pollution source; it becomes an intermediate node in an energy-fertility-soil cycle.

The value of the biogas pathway should not be narrowed to the idea that “manure becomes energy.” If energy revenue is overemphasized, biogas engineering may be reduced to a tool of resource monetization and may even generate a misleading conclusion: as long as manure can produce electricity or gas, livestock production can continue to expand, and more manure becomes more valuable. This article must draw a clear methodological boundary here. The real significance of the biogas pathway is that it provides an accommodation mechanism for existing animal metabolic residues.

It should not become a reason to encourage higher-density, larger-scale, and more externality-intensive livestock expansion. It serves system rebalancing, not a renewed industrial impulse.

More importantly, the biogas pathway can build new connections among animal metabolism, manure treatment, energy supply, and soil return. After anaerobic digestion, the gaseous fraction can enter energy-use pathways, while digestate may still enter fertilizer use and soil-improvement pathways under appropriate treatment and safety assessment. The energy, nutrients, and organic matter in manure therefore need not be treated as a single category of waste. They can be separated and used across different links: combustible gas enters the energy system, remaining solid and liquid fractions enter fertility and soil systems, and the treatment process itself reduces unorganized emissions and pollution risks. The deeper value of the biogas pathway is thus that it disaggregates the “emission end” into multiple accommodatable pathway ports [10].

From the perspective of system rebalancing, whether biogas engineering is genuinely sustainable depends on whether it is embedded in regional agricultural circulation, not merely on its energy-output efficiency. If a biogas project exists in isolation and only handles large amounts of manure generated by concentrated livestock production, without changing feed externalization, excessive stocking density, insufficient land absorption, or difficulties in manure return, it can only relieve part of the tail-end pressure. It cannot repair the agricultural pathway itself. By contrast, if biogas engineering is coordinated with regional forage production, appropriate livestock density, manure return, soil organic-matter improvement, and rural energy substitution, it may become a key connector in an animal-energy-soil cycle. In this sense, the biogas pathway is not simply a pollution-control technology. It is infrastructure for reorganizing agricultural metabolic pathways.

6.3 Biological-interaction pathways: making methane a substrate for another life process

Beyond engineered collection and energy use, methane can also enter biological-interaction pathways. In nature, methane-oxidizing microorganisms can use methane as a carbon and energy source. Under certain conditions, they can convert methane into microbial biomass, which may further enter potential pathways such as microbial protein, biological manufacturing, novel feed ingredients, biomaterials, or environmental purification. Instead of treating methane only as an emission that must be suppressed, it is worth asking whether another life process can accommodate it, converting the metabolic outlet of one system into the input of another [11][23-24].

This line of thought is highly consistent with the methodological position of this article. Not all problems need to be solved only through suppression, elimination, or reduction. Many so-called problems arise because their pathways lack subsequent accommodation, causing them to accumulate, leak, or amplify at a certain point. If a next life process can be designed for them, they may shift from externalities to circular nodes. Methane-oxidizing bacteria, microbial protein, and biofilter systems are significant precisely because they offer a non-enemy-based governance imagination: not simply negating methane formation, but finding another life process that can use methane; not only emphasizing emission reduction, but emphasizing the relay of metabolic products across different biological processes.

In pathway terms, biological interaction seeks to connect "metabolic residue-another microorganism-new biomass-feed or material" into a continuous chain. Methane, as the metabolic outlet of a previous system, can become the substrate of a subsequent system. Methane-oxidizing microorganisms may transform it into microbial biomass, which can then potentially enter protein, feed, or material systems. Methane, originally interpreted as an emission endpoint, is rewritten as the beginning of another biological process. The theoretical significance of this conversion is greater than any single technology, because it expresses a shift from endpoint thinking to relay thinking [11][23].

This biological-interaction pathway should not be exaggerated beyond its system boundaries. The existence of methane-oxidizing microorganisms does not mean that all agricultural methane can easily be converted into microbial protein. Nor does the potential of a technology eliminate the need to address collection efficiency, gas concentration, reaction conditions, energy input, economic cost, and safety evaluation. The point is not to claim that any specific technology can replace all mitigation strategies. The point is methodological: when governing metabolic products in living systems, one should first ask whether biological accommodation, biological transformation, and ecological re-embedding are possible, rather than immediately closing the object into the category of pollutant or waste.

The core value of biological-interaction pathways is therefore not the technical terminology itself, but the repositioning of methane within a network of life processes. Methane is no longer only a burden escaping from ruminants or manure systems. It can become the substrate of another class of microorganisms. Microorganisms are no longer only objects of governance; they may also become governance partners. Agriculture is no longer only an emitting sector; it may become a composite system that co-generates food, energy, microbial resources, and environmental services. This is a concrete expression of the argument that there are no natural enemies, only pathways requiring reorganization.

6.4 Synthetic-fuel pathways: from manure biogas to higher-order energy accommodation

Biogas produced from manure can also move beyond direct electricity generation, heating, or biomethane use. Through further purification, reforming, and conversion, it may enter higher-order energy pathways. For example, biogas can be transformed into syngas and then into liquid fuels, sustainable fuels, or other chemical-energy routes. In such pathways, agricultural metabolic residues may shift from low-value pollution-treatment objects to feedstocks for higher-level energy industries. Manure from cattle, pigs, and other livestock thus undergoes a change in systemic identity. It is no longer only a burden to be handled after production, but may become an upstream resource in energy-conversion chains. Farms are no longer merely emission sources; they may become nodes supplying feedstock for regional energy systems.

This line of thought expands the imagination of agricultural modernization. Conventional modernization often treats agriculture as a sector that produces food and raw materials, while energy is supplied mainly by coal, oil, natural gas, wind, solar, hydropower, and other systems. From the perspective of pathway reconstruction, agriculture produces not only grain, milk, meat, and fiber. Through manure, straw, biogas, and biomass transformation, it can also participate in energy systems. Agriculture’s function is then no longer limited to food supply. It becomes a composite system of food production, energy recovery, soil improvement, waste management, and environmental services. Methane governance is no longer only about reducing emissions. It becomes an entry point for transforming agriculture from a single-output production sector into a multifunctional circular system.

However, synthetic-fuel pathways require a clear methodological boundary. The argument is not that “more manure is better,” nor that resource utilization itself should become the final goal. If the pursuit of fuel production encourages higher-density livestock production, larger manure generation, and stronger industrial expansion, it recreates pathway mismatch. In other words, if energy valorization becomes a justification for expanding metabolic pressure, then a technical pathway originally intended to internalize externalities may become a new mechanism for producing externalities. Such development does not align with system rebalancing.

The true significance of synthetic-fuel pathways is that when agricultural metabolic residues have clear accommodation pathways, systemic externalities can be partially internalized. The aim is not to enlarge emission sources. It is to process metabolic residues that already exist or are inevitably generated within reasonable agricultural scales. It is not to allow livestock systems to expand without boundaries, but to organize animal metabolism, manure management, energy recovery, and regional circulation at a higher level. Synthetic-fuel pathways must be subordinated to regional carrying capacity, animal health, safe manure treatment, and soil-circulation needs. They cannot be allowed to dominate the agricultural system in reverse.

From this perspective, synthetic-fuel pathways offer a possibility of higher-order accommodation. Compared with direct emission, they increase the organizational level of energy contained in methane and manure. Compared with ordinary pollution treatment, they create opportunities for agricultural metabolic residues to enter energy systems. Compared with energy valorization alone, they must still be incorporated into the broader framework of system rebalancing. Their value does not lie in proving that a specific technology is advanced in itself. It lies in showing that many metabolic residues in agricultural systems need not be treated only as tail-end governance problems. Through pathway reconstruction, they may enter higher-level energy and material systems.

6.5 High-value methane pathways: the same molecule has different value under different organization

The difference in methane value can be further illustrated by comparing different methane products and application settings. Liquefied natural gas is mainly used in urban gas supply, transport fuels, industrial fuels, power generation, and heating. High-purity methane, by contrast, may enter more precise manufacturing systems, including chemical vapor deposition, semiconductor materials, photovoltaic materials, and other high-end industrial processes. Although these applications are all related to methane at the molecular level, their economic value, technical properties, and industrial positions differ sharply because of differences in purity requirements, preparation processes, transport modes, use scenarios, and system organization.

This further shows that methane value is not fixed. The same methane molecule appears as a greenhouse gas when it escapes in an unorganized manner, as a fuel when it enters an energy system, and potentially as a high-end manufacturing feedstock when it enters a high-purity gas system. The difference does not arise because the molecule itself has changed, but because it has entered different pathways, received different degrees of organization, and met different system demands. The clearer the pathway, the more refined the organization, and the more specific the application scenario, the more likely methane is to shift from liability to asset. The more fractured the pathway, the weaker the organization, and the more disorderly the escape, the more methane appears as environmental risk and governance cost.

For agricultural methane governance, this judgment has important methodological significance. Modernization should not simply compress agricultural emissions into several assessable indicators. Nor should it merely convert waste into a low-value resource. It should improve the agricultural system's capacity to identify, separate, transform, and accommodate metabolic products. A mature system does not place all metabolic products under the single label of "pollution." Nor does it treat all resource-use pathways as automatically advanced. It determines which pathway a substance should enter under specific purity levels, scales, technical conditions, and regional needs, what value it may form, and what risks it may carry.

High-value methane pathways do not imply that agricultural methane can directly, universally, and cheaply enter high-end manufacturing. Methane from agricultural sources often faces constraints in concentration, collection, purification, impurity control, and cost, and cannot be simply equated with industrial-grade or electronic-grade methane supply. The purpose of invoking this distinction is not to exaggerate the direct high-end manufacturing potential of agricultural methane. It is to show that the same substance can have different systemic identities under different forms of organization. For agriculture, the more realistic implication is to improve pathway separation for methane and organic residues, so that methane from different sources, concentrations, and treatment conditions can enter relatively suitable pathways in energy, biological conversion, environmental governance, or regional circulation, rather than escaping without organization.

The core of methane governance is therefore not only “how much less is emitted,” but “which pathway it enters.” Pathway determines value; organization determines risk; system design determines whether methane becomes liability or asset. This is especially important for agricultural modernization. A genuinely sustainable agricultural system must not only reduce externalities, but also improve internal accommodation capacity. It must not only handle emission outcomes, but also reconstruct metabolic pathways. It must not only pursue technical efficiency, but also determine whether technology serves animal health, soil recovery, energy circulation, and regional resilience.

6.6 Designing the next life for metabolic products

The core conclusion of this section is that methane should not be understood only as an emission endpoint. It should be understood as an intermediate node in a cycle that has not yet been sufficiently accommodated. As a metabolic product of ruminant anaerobic fermentation and manure transformation, methane appears as a greenhouse gas and environmental pressure when it escapes without organization. In different accommodation pathways, however, it may enter biogas energy systems, biological-interaction pathways, synthetic-fuel routes, high-value gas applications, soil-fertility return, and regional circulation. Methane’s systemic identity is therefore not static. It is redefined through pathway organization.

The task of sustainable agriculture is to design the next life for such metabolic nodes. This “next life” is not merely a metaphor for resource use. It means that metabolic products should not be cut off at the emission end, but should, wherever possible, enter subsequent material, energetic, biological, or ecological processes. Methane can enter energy systems. Manure can enter biogas and soil pathways. Methane can become a substrate for methane-oxidizing microorganisms. Biomass can be converted into fuel or materials. Treated residues can return to land. Only when these pathways are reasonably organized does agricultural modernization cease to be a process that continuously generates externalities and become a process that continuously strengthens internal accommodation capacity.

Resource utilization, however, is not the final goal in this article. It is one form of pathway governance. The argument is not to expand manure generation for the sake of resource use, nor to use energy revenue to conceal ecological pressure from high-density livestock production, nor to convert all metabolic products unconditionally into industrial feedstocks. The real core is to prevent life metabolism from being cut off at the emission end, to provide metabolic outlets with subsequent accommodation, to internalize systemic externalities as far as possible, and to move agricultural production from a linear structure of “input-production-emission-treatment” toward a circular structure of “input-metabolism-accommodation-return.”

This section has therefore completed the conceptual shift from reducing methane to accommodating methane. The biogas pathway shows how manure can enter energy systems. The biological-interaction pathway shows how methane can become the substrate of another life process. The synthetic-fuel pathway shows how agricultural metabolic residues can enter higher-order energy accommodation. The high-value methane pathway shows how the same molecule has different value under different forms of organization. Together, these pathways support a single judgment: the problem is not the methane node itself, but whether it is accommodated, transformed, and re-embedded in systemic circulation.

The deeper goal of methane governance is therefore not to build a more sophisticated suppression system for emissions, but to strengthen the agricultural system's capacity for pathway accommodation. On this basis, the next section turns to agricultural system rebalancing. If methane can be reframed as an insufficiently accommodated metabolic node, then system rebalancing cannot be completed only at the energy end, nor only at the emission end. It must simultaneously include animal health, microbial networks, soil return, energy use, and regional carrying capacity. Only through coordination among these dimensions can enteric methane governance move from a single mitigation indicator toward the systemic reconstruction of sustainable agricultural modernization.

7 Agricultural System Rebalancing: From a Single Mitigation Indicator to Animal-Microbe-Soil-Energy Coordination

7.1 The animal dimension: mitigation must not disrupt physiological stability

If rumen methane is first a metabolic outlet of anaerobic fermentation rather than an external pollutant that can be isolated from the living system, then methane governance must begin with the animal itself. A ruminant is not an "emission machine." It is a living organism with complex physiological rhythms, digestive structures, microbial symbioses, and behavioral needs. Its ability to convert grasses, straw, and other fibrous biomass that humans cannot directly utilize into milk, meat, manure, and agricultural cycling depends precisely on rumen structure, rumination behavior, microbial cooperation, and metabolic stability [7-8]. Any methane governance strategy that targets ruminants must therefore treat animal health as a boundary condition and systemic baseline, not as a secondary consideration.

Under a single-indicator mitigation logic, the governance target is easily compressed into one objective: lowering methane production. This target is measurable and comparable, but it does not automatically mean that the system has improved. If an intervention reduces methane production while impairing feed intake, digestibility, rumen pH, volatile fatty acid profiles, rumination behavior, immune status, or milk and meat performance, then the intervention requires reassessment. It may not have reduced systemic cost at all. Instead, it may have transferred environmental pressure from the atmosphere into the animal body, making the animal absorb the uncounted cost through digestive disorder, metabolic stress, declining productivity, or increased health risk [13][15].

Methane governance should therefore not be judged by emissions alone. It must also examine the animal's physiological condition. Whether feed intake remains stable, whether feed conversion improves, whether rumination behavior remains normal, whether rumen fermentation remains steady, whether milk or meat production is negatively affected, whether immune resilience is weakened, and whether disease risk increases should all become basic criteria for evaluating the sustainability of a mitigation strategy. This is especially important when feed additives, ration reformulation, microbial regulation, or other biotechnological interventions are used to affect methane generation. Such interventions must be assessed according to their compatibility with ruminant physiology, not only according to short-term mitigation effects [13][18].

From the methodological standpoint of this article, animal health is not an additional condition outside mitigation; it is a core component of system rebalancing. If the animal develops new health risks because of ration design, additive intervention, or microbial disturbance, then the apparent reduction in atmospheric emissions may be built upon internal physiological imbalance. Such governance does not truly reorganize metabolic pathways. It merely changes where imbalance becomes visible: from air to animal body, from the environmental governance ledger to the animal health ledger. In that case, the system has not been reconciled.

A sustainable approach to methane governance must therefore treat the animal as a living node within the agricultural system, not as a production device passively subjected to technical modification. The goal should not be simply to make the animal "emit less," but to optimize feed input, microbial structure, manure pathways, and energy accommodation while maintaining animal health, digestive stability, and appropriate production. The animal dimension thus establishes a fundamental boundary: any strategy that obtains lower emissions at the cost of physiological stability cannot be directly equated with agricultural modernization. Genuine modernization requires a higher level of pathway organization between animal health and environmental governance.

7.2 The microbial dimension: from eliminating microbes to regulating microbial networks

If animal health is the biological boundary of methane governance, then the rumen microbiome is the key mediator for understanding methane formation. The rumen is not a single reaction chamber. It is a dynamic network composed of bacteria, archaea, fungi, protozoa, and other microbial groups. Fiber degradation, starch breakdown, protein transformation, volatile fatty acid production, hydrogen release, and methane formation are not completed by one microbial group alone. They emerge from interaction, competition, symbiosis, and metabolic relay among multiple microbial communities. If methane governance targets one microbial group for isolated elimination, it risks ignoring the system-wide response of the rumen network.

Methanogenic archaea, fiber-degrading bacteria, fungi, and rumen protozoa are embedded in complex relationships. Methanogens are closely related to hydrogen flow and carbon dioxide reduction; fiber-degrading bacteria break down plant cell walls; fungi contribute to the disruption of fibrous structures; protozoa may influence bacterial populations, nitrogen cycling, and fermentation rhythm. These microbes do not form a simple linear causal chain. They jointly occupy a highly sensitive anaerobic ecosystem [5-6][12]. If one group is directly defined as the "problem object" and suppression or removal becomes the dominant strategy, the network may produce compensatory responses, causing the problem to reappear at another metabolic position.

The sophistication of future agricultural biotechnology should therefore not be measured by how many microbes it can kill or how much single activity it can suppress. It should be measured by whether it can understand and regulate microbial networks. Regulation here does not mean crude control. It means guiding microbial relationships more precisely and more cautiously according to feed structure, rumen environment, animal condition, and production goals. Improving forage quality, adjusting the forage-to-concentrate ratio, stabilizing feeding rhythms, maintaining rumen pH, and supporting beneficial fiber degradation may align better with systemic stability than simply removing a microbial group. The goal of microbial regulation is not to create a "methane-free rumen," but to identify a more appropriate metabolic pathway between animal health and environmental accommodation.

This requires researchers and governance actors to move from enemy thinking to relational thinking. Enemy thinking tends to define methane-associated microbes as objects to be eliminated. Relational thinking first asks under what conditions these microbes perform normal functions, under what conditions they are amplified into risks, and under which upstream inputs and downstream accommodation structures their functions shift. The former leads to single-point suppression; the latter leads to network regulation. The former focuses on short-term indicator improvement; the latter focuses on long-term stability. For living systems, the latter is closer to sustainable governance.

The microbial dimension therefore reinforces the central argument of this article: the problem does not lie in the intrinsic harmfulness of a given node, but in whether its pathway has become imbalanced. Methanogenic microbes are not natural enemies, and rumen protozoa are not natural enemies. They are relational beings within the rumen microbial network. Only by understanding these relations can technology avoid becoming a new source of systemic disturbance and instead become a tool for agricultural system rebalancing. The maturity of biotechnology does not lie in simplifying living systems into removable parts, but in recognizing the position, function, and risk boundary of each living node under different systemic conditions.

7.3 The soil dimension: manure return determines whether the material cycle is completed

Methane governance remains incomplete if it stays only inside the animal body or within the livestock facility. Ruminant metabolism does not end in the rumen, nor does it end with the formation of animal products. After animals consume plant-based materials, part of the input is converted into milk, meat, and energy for body maintenance, while another part enters the external environment as manure and other metabolic residues. If manure is properly treated, it can become organic fertilizer, digestate, slurry, and a source of soil organic matter. If poorly managed, it can become a source of methane, odor, water pollution, pathogen risk, and public governance costs [3][10]. The identity of manure is therefore not determined by its material form alone, but by its subsequent pathway.

Soil has an irreplaceable accommodation function in this process. Agricultural systems form cycles not because animals alone complete material transformation, nor because energy systems alone utilize residues, but because animal metabolic outputs can eventually return to land in appropriate forms, replenish organic matter, improve soil structure, maintain fertility cycles, and support the next round of plant growth. If manure cannot return to land, or if it returns unsafely, excessively, or at the wrong time, then the animal-feed-manure-soil cycle is broken. Under such conditions, the more concentrated the livestock system becomes, the greater the manure pressure; the weaker the soil accommodation capacity, the more easily externalities appear.

Methane governance must therefore be linked to soil governance. A strategy that discusses mitigation only at the livestock end while failing to address manure return and soil accommodation is incomplete. Even if some technologies reduce enteric methane production, the agricultural system remains imbalanced if manure is still stored in the open, discharged disorderly, or over-applied to limited land. Conversely, if manure enters soil pathways through anaerobic digestion, composting, hygienic treatment, nutrient balance calculation, and appropriate land application, it may shift from pollutant to fertility resource [10]. Soil is not the external background of agriculture; it is the key receiving end that determines whether metabolic pathways can close.

From a systemic ledger perspective, the soil dimension requires a recalculation of the real costs and real benefits of livestock production. If expanded livestock production generates more milk and meat while also causing unmanaged manure accumulation, soil overload, water pollution, and methane leakage, this expansion cannot simply be treated as efficiency improvement. Conversely, if a certain scale of ruminant production can form a loop with local forage production, straw utilization, manure return, soil organic matter improvement, and energy recovery, then animal metabolism may become part of regional agricultural circulation. The key is not whether manure exists, but whether manure has a safe, continuous, and accommodative return pathway.

The soil dimension thus pulls methane governance back from a “gas emission issue” to a “material circulation issue.” Methane is one visible expression of a broken material pathway. The deeper question is whether animal metabolic outputs can re-enter land systems, whether agricultural production operates within soil carrying capacity, and whether manure can be transformed from a governance burden into an ecological asset. Only when soil becomes a core receiving end in governance design can agricultural system rebalancing mean more than reducing gas emissions. It becomes the restoration of material closure among animals, plants, microbes, and land.

7.4 The energy dimension: agriculture is not only an energy consumer but can also be an energy producer

In industrialized agricultural systems, agriculture is often viewed as an energy consumer. Feed production requires machinery, fertilizers, pesticides, and transport. Livestock production requires electricity, fuel, heating, ventilation, and processing. Product distribution depends on cold chains, logistics, and packaging. Agriculture appears to draw power mainly from external energy systems while generating emissions and waste. Yet when manure enters biogas, syngas, sustainable fuel, or biomethane pathways, the energy identity of agriculture changes. It is no longer only an energy consumer; it may also become a regional energy producer and a participant in energy circulation [10][20].

This shift has two meanings. On the one hand, it can reduce unorganized emissions. Methane that might otherwise escape from manure storage, wastewater treatment, or anaerobic environments can be collected and used, lowering the risk of direct atmospheric release. On the other hand, it can strengthen the energy self-sufficiency of agricultural systems. Biogas power generation, heating, biomethane, and other energy conversion pathways can provide part of the energy needed by farms, villages, or regional agricultural facilities, reducing dependence on external fossil energy. Methane accommodation thus becomes not only an environmental governance issue, but also part of agricultural energy restructuring [10].

However, the energization of agriculture must serve system rebalancing rather than becoming a new worship of efficiency. If manure-to-energy pathways are understood merely as new sources of profit, they may create a dangerous reverse incentive: expanding livestock density to obtain more energy feedstock, generating more metabolic residues to increase energy output, and using resource recovery revenue to ignore land carrying capacity and animal health. In that case, a technical pathway originally designed to reduce externalities may stimulate new industrial expansion. The energy accommodation discussed here is not an argument for producing more manure for energy income. It is a way to design downstream pathways for existing metabolic residues and for the unavoidable residues generated under reasonable livestock scale.

The real significance of the energy dimension lies in establishing accommodation mechanisms for agricultural metabolic residues, not in pushing agriculture into a higher-intensity output logic. Agricultural energy production should be grounded in regional carrying capacity, animal health, safe manure treatment, and soil return. The value of biogas, syngas, or biomethane is not measured solely by energy yield, but by whether they help the agricultural system reduce unorganized emissions, strengthen internal circulation, lower external energy dependence, and form a more stable relation with soil and regional ecosystems.

The energy dimension therefore shows that agricultural modernization should not be understood only as mechanization, scale expansion, and input intensification. It can also be understood as the improvement of agriculture’s capacity to organize its own metabolic residues. When agriculture can incorporate manure, straw, biogas, and organic residues into energy circulation, it moves from passively accepting mitigation pressure to actively participating in regional circular reconstruction. Such energization does not replace the living nature of agriculture; it provides downstream accommodation for life metabolism, allowing animal metabolism, energy use, and environmental governance to be connected at a higher systemic level.

7.5 The regional dimension: organizing livestock scale according to land carrying capacity

Agricultural system rebalancing ultimately has to be grounded at the regional scale. Animal health, rumen microbiology, manure treatment, and energy recovery cannot be discussed apart from the land, water resources, forage supply, climate conditions, environmental capacity, and industrial structure of a specific region. The number of cattle, sheep, or other ruminants that a region can support should not be determined only by market demand, short-term profit, investment capacity, or single-technology efficiency. It should also be determined by forage availability, manure absorption capacity, soil carrying capacity, water resources, energy recovery capacity, and ecological environmental capacity. If livestock scale exceeds regional carrying capacity, the overall system may remain imbalanced even if emissions per animal decline [3][9].

Regional carrying capacity is crucial because many agricultural externalities do not fully appear at the scale of a single animal or a single farm. A farm may use technology to reduce part of its emissions, but if regional livestock numbers are too high, feed is imported at scale, manure cannot be absorbed by local land, and water and air remain under continuous pressure, systemic risk will still increase. Under these conditions, high-efficiency production may merely transfer real costs to the regional ecosystem, future governance systems, and future soil quality. Regional accounting is therefore closer to a real assessment of agricultural sustainability than the efficiency calculation of any single producer.

From this perspective, agricultural modernization is not more advanced simply because it becomes larger. It is more advanced when its pathways are more closed, its metabolic residues are more accommodable, and its risks leak less into the environment. Genuine modernization is not high efficiency detached from land carrying capacity; it is high-level organization that respects land carrying capacity. A region that determines appropriate livestock scale according to local forage resources, arranges manure return according to soil and crop demand, builds biogas and other recovery facilities according to energy conditions, and controls pollution risk according to environmental capacity may have greater systemic stability even if it is not the largest producer. Conversely, a region that pursues herd numbers, turnover speed, and market share while failing to accommodate manure, energy, and soil pressure carries obvious pathway mismatch.

Regional rebalancing requires animal numbers, feed sources, manure pathways, soil restoration, and energy systems to be assessed in the same systemic ledger.

Animal numbers cannot be separated from forage sources; feed sources cannot be separated from land use; manure pathways cannot be separated from soil accommodation; energy recovery cannot be separated from livestock scale; environmental capacity cannot be separated from industrial layout. Only when these factors are jointly accounted for at the regional level can methane governance become more than local optimization of a single link and instead become an adjustment of the agricultural system’s mode of organization.

The regional dimension therefore provides the integrating boundary for the animal, microbial, soil, and energy dimensions. The animal dimension requires governance not to pressure living subjects; the microbial dimension requires governance not to crudely eliminate nodes; the soil dimension requires metabolic residues to have a receiving end; the energy dimension requires metabolic products to have accommodation pathways; and the regional dimension requires all these pathways to be designed within land carrying capacity and ecological capacity. Only when a regional systemic ledger is established can agricultural modernization move from “single-efficiency improvement” to “overall pathway closure.”

7.6 Rebalancing is not anti-technology; it redirects technology

This chapter has shown from five dimensions-animal, microbe, soil, energy, and region-that rumen methane governance should not remain confined to a single mitigation indicator. It should move toward agricultural system rebalancing. The animal dimension emphasizes that mitigation must not destroy physiological stability. The microbial dimension emphasizes that governance should not begin from microbial elimination, but from understanding and regulating microbial networks. The soil dimension emphasizes that manure return determines whether agriculture completes material closure. The energy dimension emphasizes that agriculture is not only an energy consumer, but can participate in energy circulation through metabolic residue accommodation. The regional dimension emphasizes that livestock scale must be governed by land carrying capacity and environmental capacity. Together, these dimensions show that methane is not an isolated gas problem, but a systemic issue produced by animal metabolism, microbial networks, material circulation, energy pathways, and regional carrying structures.

The “rebalancing” proposed here is therefore not a mild compromise, nor a vague mediation between development and environmental protection. It does not simply say that agriculture should both produce and reduce emissions. Rather, it requires a redefinition of technological direction, governance objects, and systemic boundaries. Rebalancing means placing the animal body, rumen microbiome, manure treatment, soil accommodation, energy use, and regional capacity-elements separated by industrialized pathways-back into one system ledger. It emphasizes pathway reorganization rather than compromise between indicators; strengthening accommodation capacity rather than suppressing a single problem.

This also means that the article is neither anti-technology nor opposed to methane governance. On the contrary, it calls for a higher level of technology. Lower-level technology tends to treat life processes as problems to be controlled, microbes as objects to be eliminated, manure as waste to be treated, and emission numbers as the sole criterion of governance success. Higher-level technology should understand life processes, design accommodation pathways for metabolic products, protect animal health, regulate microbial networks, promote soil restoration, recover energy, and reduce regional externalities. The former serves single-indicator suppression; the latter serves system rebalancing.

Agricultural system rebalancing therefore requires technology to move from “lowering emission numbers” to “reorganizing metabolic pathways,” from “clearing problem nodes” to “enhancing system accommodation capacity,” and from “improving short-term efficiency” to “maintaining long-term resilience.” Only in this sense can technology become a true component of sustainable agricultural modernization. Otherwise, the more advanced technology becomes, the more efficiently it may transfer externalities; the more refined governance becomes, the more precisely it may relocate imbalance. What matters is not pushing the methane problem down in an indicator table, but restoring sustainable pathway relations among animals, microbes, soil, energy, and regional circulation.

This chapter thus advances the argument from pathway accommodation to systemic coordination. Chapter 6 argued that methane should enter a next cycle; this chapter further shows that such a cycle cannot be completed only at the energy end, nor can it rely on a single technology. It must be constrained and coordinated by animal health, microbial networks, soil accommodation, energy pathways, and regional carrying capacity. Only when these dimensions work together can rumen methane governance move from a single mitigation project toward a methodological reconstruction of agricultural modernization. The final chapter will therefore return to the core judgment of the article: sustainable agriculture is not about finding enemies, but about reorganizing pathways that have not yet been accommodated; it is not about denying life metabolism, but about rebuilding a more stable, more continuous, and less leaky relationship between life and technology.

8 Conclusion: From Eliminating Enemies to Reorganizing Unaccommodated Pathways

8.1 Main conclusion: rumen methane as a systemic signal of imbalanced agricultural modernization

This article has taken rumen methane not as a narrow livestock mitigation issue, but as a micro-level entry point for rethinking the systemic relations among life metabolism, material circulation, energy use, and environmental governance in agricultural modernization. Its central argument is that rumen methane is not an isolated emission problem. It is a visible signal of imbalance among animal metabolism, microbial ecology, feed inputs, manure management, soil accommodation, and energy pathways in modern agricultural systems. Methane becomes a governance pressure not merely because ruminants produce it during anaerobic fermentation, but because modern agriculture places this metabolic process within high-density livestock production, externalized feed dependence, concentrated manure discharge, insufficient land accommodation, and broken energy pathways. A metabolic outlet with a physiological position is thereby amplified into an environmental externality [1-3].

Methane governance therefore cannot be confined to the emission end, nor can its objective be reduced to asking how much methane can be reduced. If solutions are sought only at the emission end, ruminants, methanogens, rumen protozoa, or manure itself are easily framed as problem objects, while the deeper pathway mismatch remains obscured. The more fundamental questions are: through which metabolic pathway is methane produced? Why is it not accommodated by subsequent systems? Does feed input fit the physiological structure of ruminants? Can manure return to soil or enter energy cycles? Do regional land, water, energy, and environmental capacities have sufficient accommodation ability? Only when these questions are addressed together does methane cease to be merely a gas-emission indicator and become a signal of whether the agricultural system can reconcile its own internal ledger.

From this perspective, the core contradiction of modern agriculture is not simply insufficient production, low efficiency, or inadequate technology. It lies in the structural mismatch between production efficiency and systemic accommodation. Agricultural modernization has increased food supply and strengthened human capacity to intervene in animals, microbes, land, and energy pathways. Yet if such intervention serves mainly scale expansion, single-factor efficiency, and indicator compression, without simultaneously building continuous pathways among animal metabolism, manure treatment, soil return, and energy accommodation, modernization itself may continue to generate new externalities. Methane is a concentrated expression of this problem. It reminds us that life processes do not lose their own logic when incorporated into industrial production, and agricultural governance cannot be designed as isolated technical intervention detached from the metabolic position of living systems.

The main conclusion of this article can therefore be stated as follows: rumen methane is a systemic signal of pathway mismatch in agricultural modernization, not an isolated problem caused by a single object. It indicates that sustainable agriculture cannot be pursued only through yield, efficiency, scale, and emission figures. It must also reconsider the relations among animal health, microbial stability, feed sources, manure return, soil accommodation, energy use, and regional carrying capacity. Only when these relations are reorganized can methane governance move from external mitigation pressure to an entry point for agricultural system rebalancing.

8.2 Theoretical contribution: from emission governance to pathway governance

The theoretical contribution of this article is to move rumen methane governance from “emission-object governance” toward “systemic pathway governance.” Conventional governance often begins with the question of how to reduce methane. It identifies emission sources, measures emission intensity, searches for suppression methods, and reduces emissions through ration adjustment, microbial intervention, additives, manure treatment, or other technical approaches. These efforts are important. However, if they remain at the level of single-point mitigation, they risk simplifying a complex living system into an emission machine, reducing microbial networks to removable objects, treating manure as waste, and equating technical success with numerical decline. This article asks a further set of questions: through which pathway does methane arise, where does that pathway break, and into what next cycle can methane enter? [4][18-19]

Pathway governance first means refusing to define nodes within living systems as enemies in advance. Methanogenic archaea, rumen protozoa, ruminants, and manure are not natural enemies. Under certain systemic conditions, they may perform normal functions; under pathway rupture, environmental pressure, or organizational imbalance, they may appear as risk sources. Methanogens participate in hydrogen and carbon transformation. Rumen protozoa may affect microbial networks and fermentation rhythms. Ruminants convert fibrous biomass into food and fertility sources usable by humans. Manure may carry energy and soil organic matter [6][10][12]. The problem is not that these objects are intrinsically harmful. The problem is whether their pathways are properly organized.

Second, pathway governance requires a shift from object removal to relational repositioning. When a node is associated with emissions, pollution, or risk, conventional governance tends to ask how to reduce, suppress, or remove it. Pathway governance asks further questions: What function does this node perform in a normal system? Under what conditions is it amplified into a problem? Has the upstream input changed its role? Is downstream accommodation missing? Has the regional system exceeded its carrying boundary? This mode of questioning moves governance away from “who is the object?” toward “how has the relationship become imbalanced?” The focus shifts from finding enemies to reorganizing relations, from deleting nodes to restoring pathways, and from reducing a single value to strengthening systemic accommodation capacity.

Third, pathway governance places resource recovery within a deeper methodological framework. Biogas, methane-oxidizing bacteria, microbial protein, synthetic fuels, high-purity methane, and related pathways are not the ultimate purpose of this article. Their importance lies not in proving that methane or manure can be monetized, but in showing that the same material can have different systemic identities in different pathways. Methane released without organization is a greenhouse gas. Methane collected and managed can become energy. Methane entering high-purity gas systems may become manufacturing feedstock. Methane entering microbial pathways may become new biomass [10-11]. Pathway determines identity; organization determines value; accommodation determines externality. Resource recovery is therefore only one expression of pathway governance. The theoretical core is how a metabolic outlet can be accommodated by the system.

The shift from emission governance to pathway governance does not deny the importance of mitigation. Rather, it redefines where mitigation belongs theoretically. Mitigation cannot stand alone apart from animal health, microbial networks, soil return, energy accommodation, and regional carrying capacity. A decline in emissions does not automatically mean systemic improvement. Only when mitigation occurs together with metabolic pathway reorganization, internalization of externalities, protection of physiological stability, and strengthening of regional resilience does it have sustainable significance [9][13]. The theoretical key is not to label objects, but to reposition relations. Governance success should not be defined by a single indicator, but by whether systemic pathways become more continuous, more accommodative, and less leaky.

8.3 Practical implications: energy, environment, and sustainable agriculture must be co-designed

The practical implication of this article is that future agricultural methane governance must jointly design animal health, microbial networks, manure recovery, soil restoration, energy use, and regional carrying capacity, rather than assigning them to separate departments, technologies, and indicator systems. Rumen methane is generated inside the animal, but it is shaped by feed structure, microbial ecology, and livestock management. Manure methane emerges outside the body, but it is tied to animal numbers, stocking density, land absorption capacity, and energy recovery systems. Methane's environmental effect appears in the atmosphere, but its governance pathway must return to agricultural production, energy use, and soil circulation. Methane governance is therefore inherently cross-systemic; it cannot be reduced to a single technical project [2-3].

At the animal level, any governance strategy should take digestive stability and overall ruminant health as the baseline. Feed adjustment, additive use, microbial regulation, and other interventions must simultaneously evaluate feed intake, digestibility, rumination behavior, rumen pH, production performance, and immune status. Methane reduction should not be achieved by creating new animal health risks. If the animal body becomes the site where the cost of environmental indicator improvement is absorbed, governance has only transferred pressure rather than rebalanced the system [13].

At the microbial level, governance should move from elimination thinking to network regulation. The rumen microbiome is a highly complex ecological network in which methanogens, fiber-degrading bacteria, fungi, and protozoa are all embedded. Future agricultural biotechnology should not define progress by its ability to eliminate a microbial group, but by its capacity to understand microbial interactions, metabolic flows, and condition-dependent functions. Only when microbial technology serves animal health and systemic stability, rather than becoming another single-point disturbance, can it acquire sustainable value [4][8][12].

At the soil level, whether manure can return to land safely, appropriately, and continuously is a crucial criterion for judging whether agriculture has completed its material loop. Manure is neither a natural pollutant nor a natural resource. Its systemic identity is determined by its subsequent pathway. Through hygienic treatment, anaerobic digestion, composting, nutrient balance calculation, and appropriate land application, manure can become a source of soil organic matter and fertility. If poorly managed, it becomes methane, odor, water pollution, and governance cost. Methane governance therefore cannot be designed only at the livestock end. It must be integrated with soil accommodation, fertility restoration, and land carrying capacity [3][10].

At the energy level, biogas, syngas, sustainable fuels, biomethane, high-purity methane, microbial protein, biofilters, and biomimetic rumen reactors should not be understood in isolation. They should serve agricultural system rebalancing. They are not inherently desirable simply because they produce value, nor are they better merely because more of them can be deployed. Each technology must answer the same set of questions: Does it improve metabolic pathways? Does it reduce unorganized leakage? Does it protect animal health? Does it strengthen soil accommodation? Does it reduce regional externalities? Does it improve long-term systemic resilience? Only technologies that can enter this chain of questions can truly serve sustainable agricultural modernization [10-11].

At the regional level, livestock scale must be constrained by land carrying capacity, forage sources, manure absorption capacity, water resources, energy recovery ability, and environmental capacity. The scale, structure, and type of ruminant production suitable for a region cannot be determined only by market demand and short-term returns. If livestock scale exceeds regional accommodation capacity, the overall system may remain imbalanced even if emissions per animal decline. Regional governance therefore needs a comprehensive ledger that accounts for animal numbers, feed sources, manure pathways, soil restoration, energy systems, and ecological capacity within the same framework [9].

Energy, environment, and sustainable agriculture must therefore be co-designed. Co-design does not mean simply adding multiple technologies together. Nor does it mean optimizing agriculture, energy, and environmental protection separately and then assembling them afterward. It means organizing life metabolism, material pathways, energy accommodation, soil return, and regional capacity as parts of the same system from the beginning. Only in this way can methane governance become more than end-of-pipe control and serve as an entry point for agricultural system reconstruction. Agricultural modernization can then move beyond production efficiency toward a system of lower externality, stronger accommodation capacity, and long-term resilience.

8.4 Final judgment: sustainable agriculture depends on rebuilding pathway relations between life and technology

Seen narrowly, methane is an emission indicator. Seen systemically, methane is a signal that the pathways among animals, microbes, soil, energy, and agricultural modernization have not yet been reorganized. This article’s repeated claim that there are no natural enemies, only pathways that have not yet been reorganized, does not mean that governance objects should disappear or that methane emissions do not create real climate and environmental pressures. It means that we should reject the premature enemy-making of functional nodes within living systems. Methanogens are not natural enemies. Rumen protozoa are not natural enemies. Ruminants are not natural enemies. Manure is not a natural enemy. They become problematic when their pathways are imbalanced, their accommodation mechanisms are missing, and their systemic relations are broken.

The key to sustainable agriculture is not to search for enemies, but to reconstruct relations. It is not to deny life metabolism, but to design a next cycle for it. It is not to reduce a single indicator, but to reorganize pathways among animal health, microbial stability, soil accommodation, energy use, and regional resilience. If governance treats methane simply as an object to be eliminated, it may achieve short-term indicator improvement while creating new problems in animal health, microbial disturbance, manure treatment, soil loading, or regional externalities. Conversely, if methane is treated as a metabolic node, and if its upstream inputs, internal formation, downstream accommodation, and regional boundaries are examined together, then methane governance can become an entry point for agricultural system rebalancing.

The article therefore does not ultimately propose a simple mitigation scheme. It proposes a methodological shift in agricultural modernization. First, governance should move from node removal to pathway diagnosis. It should not rush to delete an object, but first determine its position, function, and conditions of imbalance within the system. Second, it should move from emission governance to pathway governance. Mitigation is not an isolated goal; it should be embedded in metabolic pathway reorganization, material return, and energy accommodation. Third, it should move from resource recovery to life-metabolism accommodation. Resource recovery is not the final purpose; the deeper question is whether a metabolic outlet can be accommodated by the system. Fourth, it should move from single-indicator optimization to system rebalancing. Governance effectiveness should not be judged only by the decline of one emission value, but by whether animal health, microbial networks, soil restoration, energy circulation, and regional carrying capacity improve together.

“There are no enemies” does not mean that agricultural governance requires no intervention, nor that all life processes should be accepted without qualification. It means that governance cannot begin from simplistic enemy-making. Many nodes in living systems gain meaning only within concrete pathways. The same node may be functional in one pathway and risky in another. “Pathways not yet reorganized” means that the real task of sustainable agriculture is to reconnect the animals, microbes, soil, energy, and regional cycles that have been severed by industrialized pathways. Metabolic products should no longer be forced to remain at the emission end. Governance should no longer be merely end-point control under external pressure. Technology should no longer function only as a tool for efficiency enhancement, but as a means of restoring systemic accommodation capacity and long-term resilience.

Rumen methane, although seemingly a small problem of biological metabolism, thus provides an entry point for rethinking agricultural modernization. It forces us to recognize that agriculture is not merely a food-production machine. It is a life-technology system composed of animals, microbes, plants, soil, water, energy, and human organization. Truly sustainable agricultural modernization does not compress life processes into controllable indicators, nor does it treat natural metabolism as an obstacle to be removed. It begins by understanding the logic of life and then designing more continuous, more stable, and less leaky accommodation pathways for each metabolic node. Only in this sense can methane governance move beyond a single mitigation project and become both a theoretical entry point and a practical support for agricultural system rebalancing and sustainable modernization.

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