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Seaweed-Derived Feed Additives for Enteric Methane Mitigation in Cattle: Efficacy Evidence, Economic Incentives, and Policy Pathways for Smallholder and Commercial Dairy Systems

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Abstract - The emissions from enteric methane by the world's 1.5 billion cattle is one of the largest and least tackled sources of agricultural GHGs. Livestock emissions are a critical factor in near term climate outcomes as methane has a global warming potential of approximately 80 times more than carbon dioxide over a 20 year time horizon. This article explores an emerging mitigation pathway natural, seaweed based feed additives that inhibit the formation of CH_4 in the rumen. It reviews peer-reviewed trials and meta analyses, dissects the biological mechanism of bromoform containing red seaweed to inhibit methanogenesis, and examines figures of actual reductions, which have been as high as 80% or more in some instances depending on the dose and conditions, as well as the economic case for adoption by smallholder farmers, dairy cooperatives, and corporate producers. The piece also places this technology in the context of changing regulations, such as the first ever livestock emissions tax in the world, which will come into effect in 2030, and the specific advantage for countries with a high number of cattle. Most importantly, it highlights unanswered questions regarding long term effectiveness, animal productivity, food safety and cost. The goal is to provide the public, policy makers and farming communities with fact based and balanced information on a technology that could be important for climate mitigation and for rural livelihoods as well.

Keywords: Enteric methane, Seaweed feed additives, Sustainable dairy farming, Climate change mitigation, Livestock emissions, Rumen fermentation, Agricultural economics, Greenhouse gas policy.

1. INTRODUCTION

Power stations, cars and planes are typically the focus when people talk about climate change. Much less consideration is given to a quiet, grazing source of warming that is found in fields on every inhabited continent. Today there are about 1.5 billion cattle in the world and each of them emits methane as an inevitable byproduct of their digestive system. One at a time it's not much. Together, it's far from. When the GHGs emitted by global cattle are aggregated and considered as a single country, they rank third in the world, after the two highest GHG emitters.

It is important for this reason because of the chemistry of methane. Methane has a lifetime of 12 years in the atmosphere, but is a much more effective greenhouse gas than CO_2 during its lifetime. The latest Intergovernmental Panel on Climate Change (IPCC) estimate is that a tonne of methane is equivalent to about eighty times the warming effect of a tonne of carbon dioxide over a twenty year period, and twenty eight to thirty times the warming effect of a tonne of carbon dioxide over a century. The fleeting power of this methane has a significant implication cutting methane emissions today has climate benefits that can be seen in a generation. There are few other interventions that have such a quick turnaround.

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Governments have started to react. The days when agricultural methane emissions were not subject to regulation are coming to an end, as one European country has passed the world's first law to tax such emissions, which will be implemented in 2030. Producers, exporters and dairy processors across the globe are closely watching, as they know that more may follow and consumer demands for the carbon footprint of milk and meat are increasing. In this context, scientists have been working on a seemingly straightforward question. Can the digestive system of cattle be tweaked to produce less methane initially One of the most promising solutions is a red seaweed feed additive. A compound found in some marine algae is found naturally which will disrupt the final biochemical step in the rumen production of methane. There have been controlled trials which have shown reductions of up to around 80% at optimum feeding rates, and around a third at normal grazing rates, while a recent meta-analysis of all available trials has estimated an average reduction of around 47% under normal feeding rates.

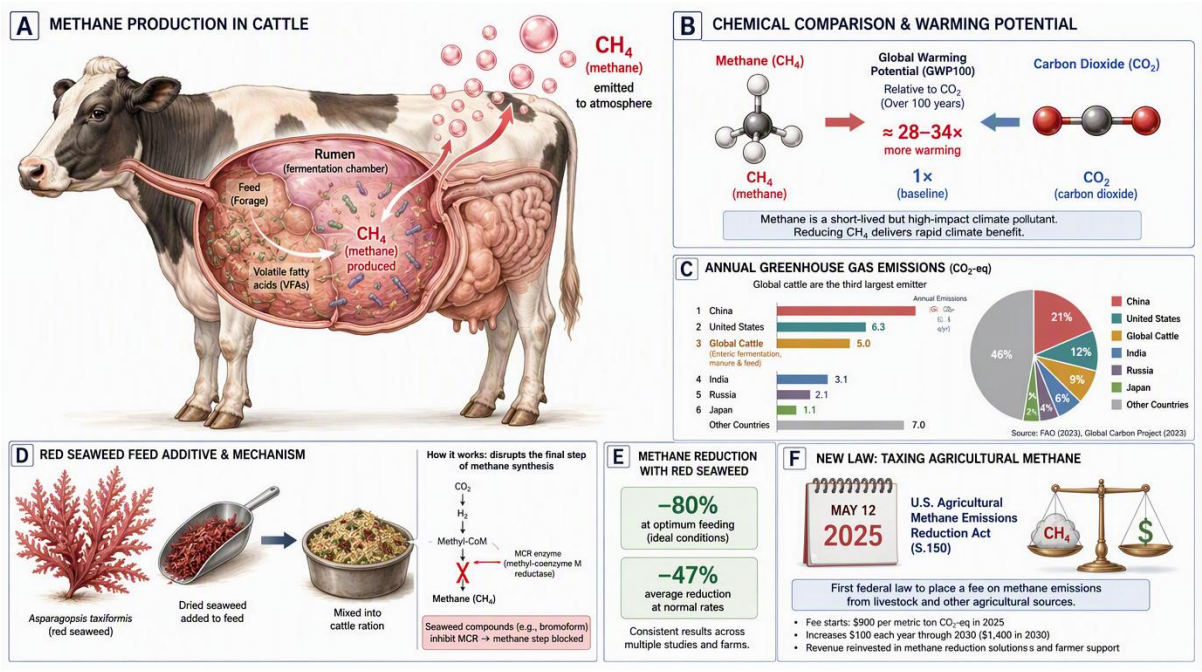

Fig -1: Chemical Comparison & Warming Potential

This article will describe in a non-technical and yet thorough manner, how this technology works, what the evidence actually reveals, the cost of this technology and who benefits. It is especially interested in the economic rationale that will drive farmers' uptake of the additive and the opportunity for countries that have very high numbers of cattle and hence very large dairy industries. It also tackles head on the remaining issues the long term effects, animal productivity, scalability, and cost which need to be resolved before this approach can realize its potential. Throughout the aim is to educate, not to lobby, and to present the facts without hyperbole, allowing the reader to draw their own conclusions about the merits of seaweed in a cow's diet as one of the serious climate solutions of our time.

2. WHY PUBLIC AWARENESS OF LIVESTOCK METHANE DESERVES SERIOUS ATTENTION

The aim of this article is to bridge one of the existing gaps between scientific knowledge and public understanding. People are well aware that fossil fuel combustion is a contributor to global warming. Even

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fewer understand that agriculture is the largest source of human induced CH_4 emissions, and that in agriculture, the majority of emissions are from the digestion of ruminant animals cattle, buffalo, sheep and goats. Approximately 80% of agricultural CH_4 is emitted from livestock systems, with almost 90% of this from enteric fermentation, which is a natural process in the animal's digestive system.

There are practical implications to this lack of awareness. Public support has an influence on policy and policy has an influence on markets. If citizens are unaware of the size of the livestock emissions, governments are not under pressure to invest in research into mitigation and farmers are not provided with the information and incentives to do so. On the other hand, if awareness is skewed through exaggeration, such as in accusations against farmers or that animal agriculture needs to be completely abandoned, it leads to polarisation instead of progress. Livestock play a vital role in the nutrition, income and social security of hundreds of millions of people, especially in developing economies. Any honest discussion should take that fact into account.

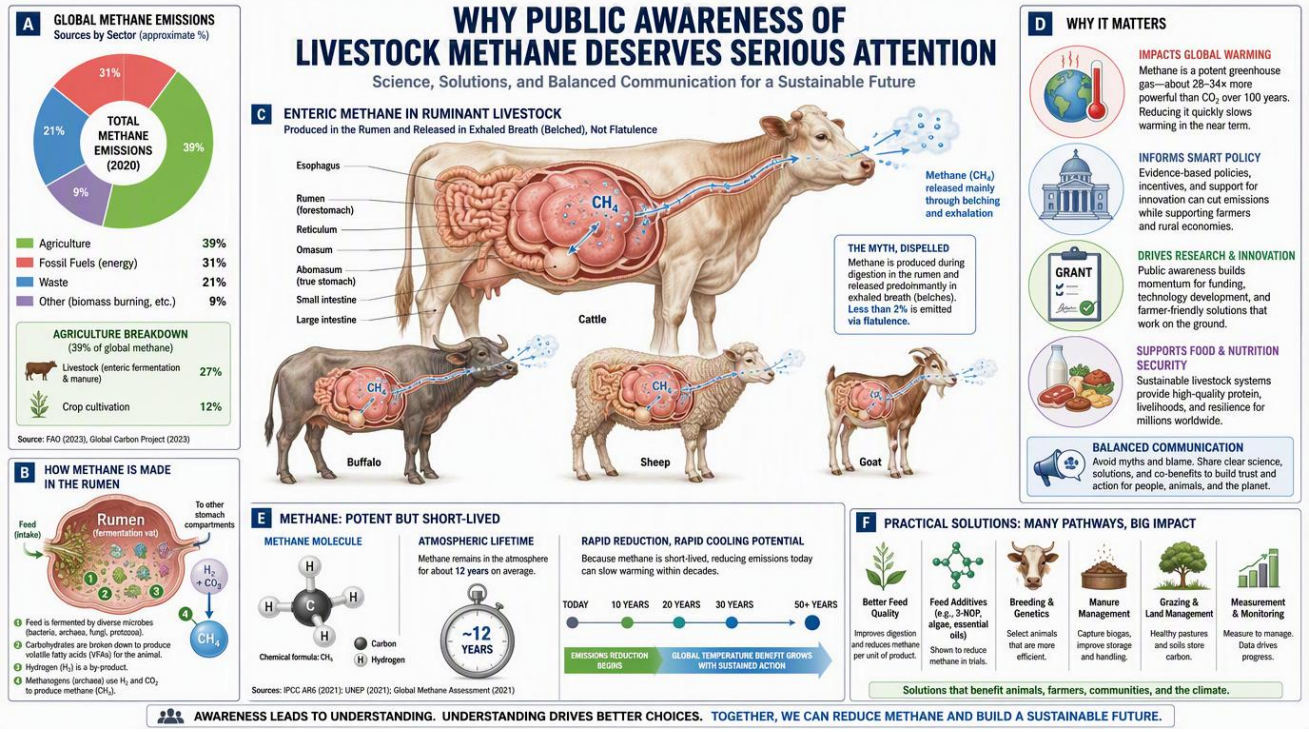

Fig -2: Public Awareness Livestock Methane Deserves Serious Attention

Another myth that needs to be dispelled right at the start is widely believed. Livestock methane is sometimes referred to as flatulence. In fact, the vast majority of enteric methane well over ninety percent is belched out, that is, the gas that is produced in the forestomach of the animal escapes upwards through the mouth and nostrils. Although this distinction might appear unimportant, it is important for the understanding of mitigation interventions need to focus on the fermentation process in the rumen and this is exactly what the feed additives mentioned in this article are designed to do.

Another excuse for citizens to be involved is time. Methane is a short-lived but powerful greenhouse gas, meaning that reduction of emissions will have cooling effects in the short term, on the order of decades, not centuries. More and more, climate scientists are stressing that the temperature targets of the Paris

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Agreement are unattainable without tackling livestock methane. However, there are few countries that have fixed reduction targets for the sector. The precondition for sensible action is an informed public, one that is able to separate what is real from what is marketing and one that is aware of the environmental issues at stake as well as the livelihoods that are at stake. The pages that follow are designed for that purpose, to provide the basis for an informed judgement.

3. THE SCALE OF THE PROBLEM COUNTING THE CLIMATE COST OF 1.5 BILLION CATTLE

To understand the extent of livestock methane, it's important to take a step back and see the big picture. This is because the world's cattle herd has increased from approximately 942 million in 1961 to over 1.5 billion today, due to the increasing demand for milk and meat from a growing and prospering human population. The amount of methane produced by a single cow is approximately 70 to 120 kilograms annually, depending on the breed, feed and management. This is a huge and continuous emission of one of the most potent GHGs known, multiplied by the huge herd of animals around the world.

Recent estimates indicate that livestock methane emissions are approximately 115 million tonnes per year, up by over ten per cent since the early 2000s and will reach 150 million tonnes per year by 2050 in the absence of policy. A peer-reviewed study, which compared livestock emissions with national inventories, found that, if considered as a country, cattle alone would be the world's third biggest greenhouse gas emitter. Total livestock emissions direct and indirect are estimated to account for 14-16% of the global total.

These numbers are multiplied by the strength of methane. The reason for this is that the gas is so effective at trapping heat that it has a disproportionately large warming impact in the near term, over the next 20 years, when humanity must turn the emissions curve in order to keep warming to 1.5 degrees on the table. The contribution of future livestock methane to warming has been demonstrated to be equivalent to approximately one third of the warming caused by all future net CO_2 emissions in mitigation pathways that are consistent with stringent temperature targets. Simply put, without accounting for livestock methane, it becomes almost impossible to do climate arithmetic.

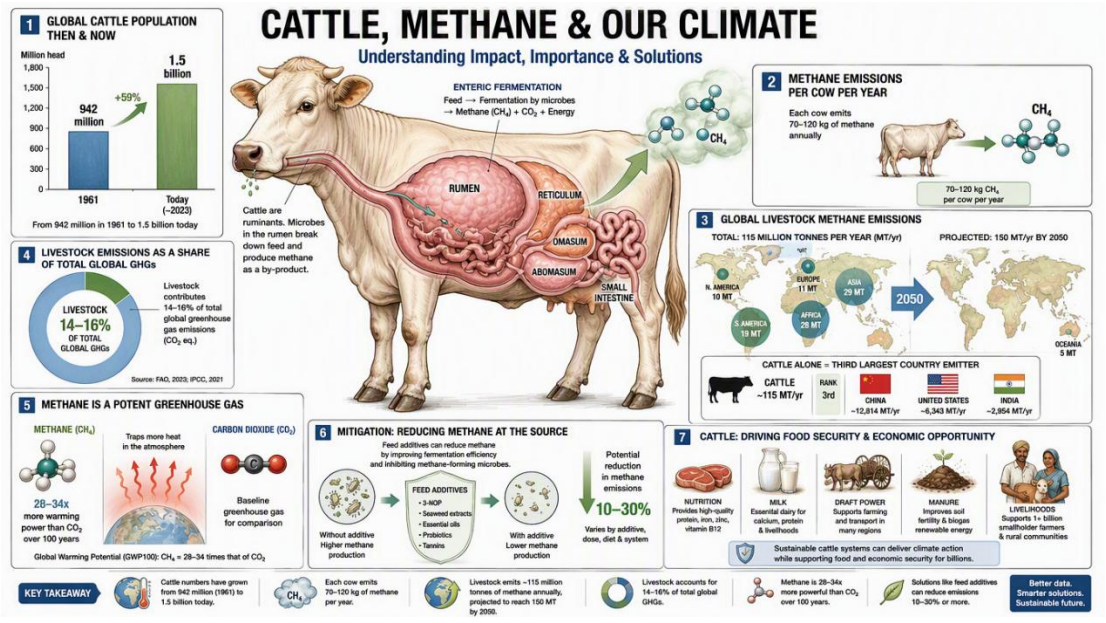

Fig -3: Cattle Methane & Our Climate

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However, it would be misleading and unfair to the farming community to paint the picture of cattle being a climate liability. Grasses and crop residues are indigestible to humans, but they are used by livestock to produce good quality protein. They power the draught, serve as manure for fertilizer and give financial security to the small holders of Asia, Africa and Latin America. However, per animal emissions are often lower in many developing countries than in intensive systems despite higher emissions per litre of milk because of lower productivity. The challenge, therefore, is not to stop farmers from producing cattle, but to separate the climate impact of each animal from the production of the livestock to enable farmers to keep producing food but to significantly reduce the climate impact of every animal. This is the question feed additive science aims to address.

4. HOW METHANE IS PRODUCED INSIDE THE RUMINANT DIGESTIVE SYSTEM

In order to understand the potential of a seaweed additive to suppress methane, it is first necessary to understand the source of the methane. Cattle are members of a remarkable group of animals called ruminants, which have a four chamber stomach, the largest part of which is a living fermentation vessel, known as the rumen. An adult cow's rumen contains more than a hundred litres and contains an extraordinary abundance of microorganisms bacteria, protozoa, fungi and a special group of microorganisms, the archaea.

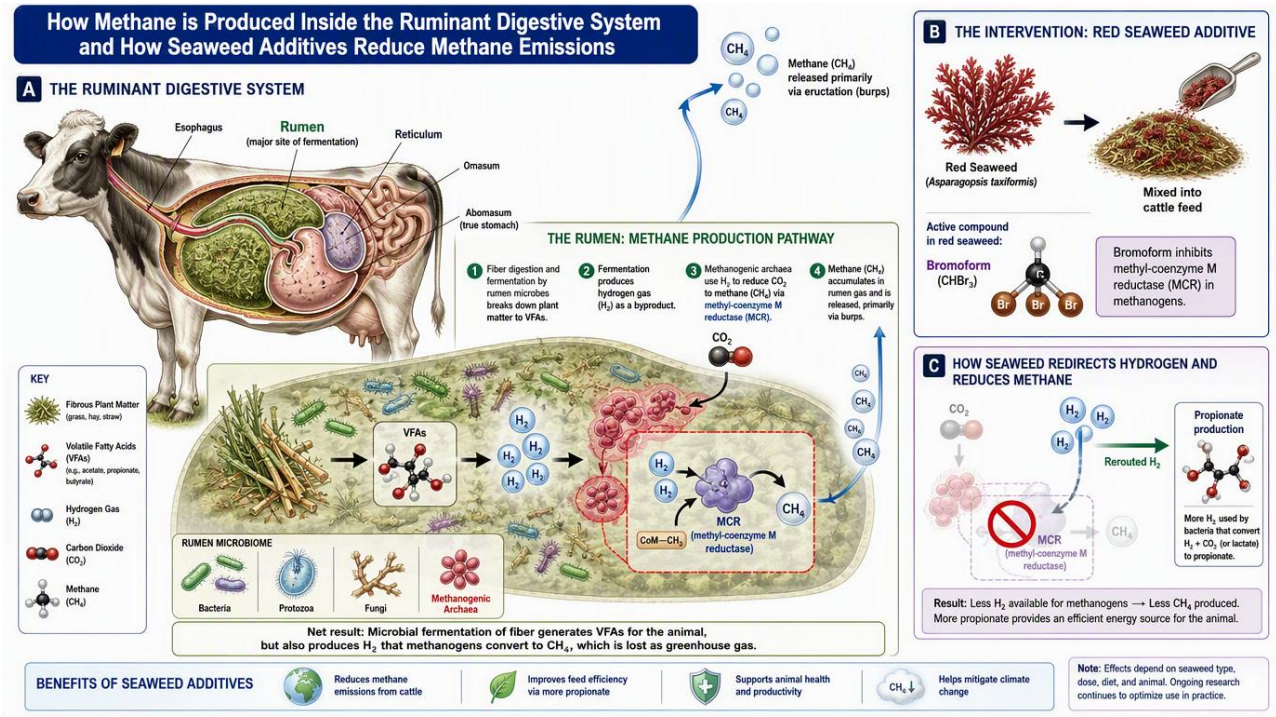

Fig -4: How Methane is Produced inside the Ruminant Digestive System

This microbial community is responsible for the ability of cattle to digest fibrous plants like grass, straw and other plants that humans cannot digest. The microbes ferment the cellulose and other complex carbohydrates into volatile fatty acids which are absorbed by the animal through the rumen wall as the animal's main source of energy. But, hydrogen gas is also produced during fermentation. The rumen ecosystem has developed a way to get rid of the hydrogen, by having specialised archaea, called

methanogens, which use hydrogen to reduce carbon dioxide into methane. This methane is then released from the animal, mainly via burps.

Methanogenesis from the cow's point of view is a biological necessity and it is an inefficiency. This methane that is expelled is lost energy, usually 2-12% of the gross energy of the animal's food is literally lost into the air. From the planet's point of view it is a steady flow of a potent warming agent. From the scientist's point of view, however, it's an opportunity, because the last step of methane formation requires a single enzyme that's very specific, and only occurs in the methanogenic archaea. The final reaction in the methane-producing pathway is catalyzed by this enzyme, called methyl-coenzyme M reductase. In principle, any compound that can inhibit the enzyme, without adversely affecting the animal or the beneficial microbes that are responsible for digestion, could turn off methane production at source.

As it happens, nature makes just these sorts of compounds. Some species of red seaweeds produce halogenated compounds, notably bromoform, as a chemical defence mechanism. These molecules are structural analogues of methane and are able to interfere directly with the important enzyme. If small amounts of the seaweed are added to the cattle feed, the methanogens are inhibited, hydrogen is diverted from methane production to other pathways e.g. propionate production and methane production drops significantly. This beautiful biochemistry, found and developed over the last 10 years, is the science that underpins the technology that this article is about.

5. METHODOLOGY

5.1 How the Evidence in This Article Was Gathered and Assessed

As a result of the plethora of positive commercial claims about climate technologies, readers should be informed of how the information was compiled and verified in this case. It is a compilation of publicly available, peer-reviewed scientific literature, official policy documents, and internationally recognised statistical sources, and has been compared to each other to identify areas of agreement and areas of true uncertainty. The global warming potential estimates for methane were based on those provided by the Intergovernmental Panel on Climate Change (IPCC) assessment reports, the internationally recognized scientific body responsible for climate metrics, and compared with estimates from environmental protection agencies and energy research organizations. Global cattle numbers and the historical increase in those numbers are based on data from agricultural statistics provided by international organisations of food and agriculture and analysed in peer-reviewed studies on livestock demography. Cattle emissions are compared with national emitters based on published academic analysis based on region specific emission factors. The evidence on seaweed based feed additives was based mainly on controlled feeding trials published in recognised scientific journals, and feeding trials under commercial grazing conditions using automated head chamber measurement systems, and respiration chamber studies the gold standard for enteric emission measurements. A recent meta-analysis of 14 separate studies with dozens of comparisons between different treatments in beef and dairy cattle was given special consideration. Meta-analysis is important because the results of individual trials vary widely due to the dose, composition of the diet, type of cattle, and method of measurement, the average effect must be estimated by combining the results of all of the trials. The information on policies was cross-checked with official government agreements and reports, and with well-known international news organisations, for example, the livestock emissions tax in a European country. What was not included in this methodology is perhaps as significant. Statements included in company marketing materials, press releases or investor presentations were not considered to be facts. Where a widely circulated claim is not backed up in scientific

literature, this article states that most notably, the claim that additives which reduce methane can increase milk yield. Costs reported that were not independently verifiable are labeled developer estimates. In line with the neutral nature of this work, no commercial entity is named, and no finding has been adjusted in favour of any industry, country or interest group. The reader thus can be put in the author's shoes and evaluate the verified evidence on its merits.

6. THE SCIENCE OF SEAWEED

6.1 How a Marine Organism Interrupts Methane Formation

This story's star is a genus of red seaweed, which can be seen in tropical and temperate oceans all over the world. It was used for food by the coastal people for centuries and in some island cuisines it is still a delicacy. However, its climate relevance is due to its unique chemistry. The seaweed focuses the halogenated compounds in special gland cells, the most prevalent being bromoform, a molecule made up of one carbon atom, one hydrogen atom and three bromine atoms.

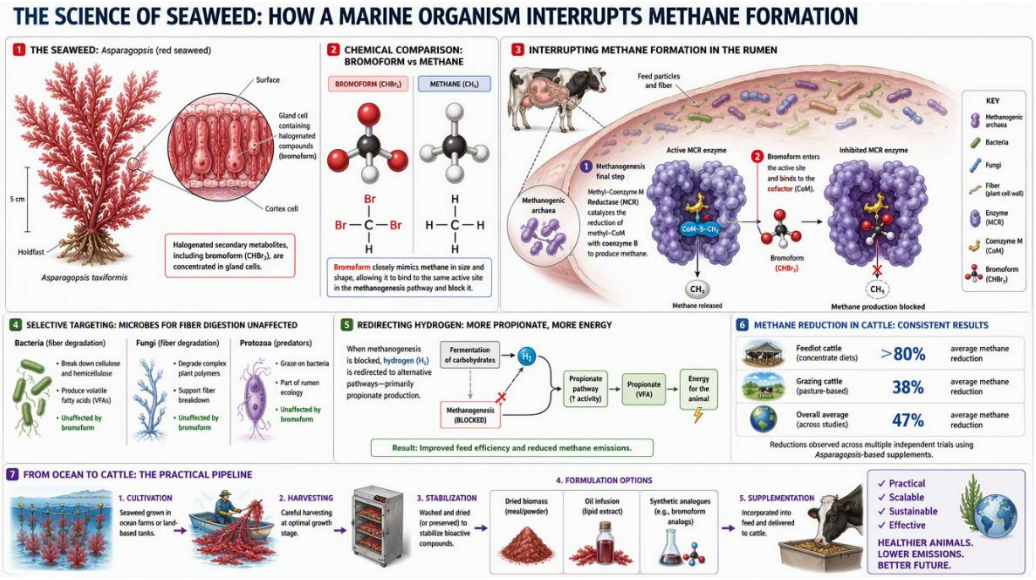

Fig -5: How a Marine Organism Interrupts Methane Formation

The structure of Bromoform is like that of methane, and it's this similarity that is the secret to its effect. Bromoform inside the rumen binds to and sequesters the cofactor that is required by the enzyme that carries out the last step in the synthesis of methane in the methanogenic archaea, called methyl-coenzyme M reductase. The enzyme is inactive and the methane assembly line comes to a standstill. Importantly, the compound is selective for targeting methanogens, meaning that the bacteria and fungi that break down fibre are not affected, and the hydrogen that would have been converted into methane is directed down other avenues, such as production of propionate a volatile fatty acid that can be used by the animal for energy. As early as laboratory experiments, it was shown that very small amounts of dried seaweed a few per cent of the animal's daily feed could under controlled conditions practically eliminate methane production. Later experiments on live animals also showed significant results in the field, with the inevitable variability that field conditions bring. In feedlot beef cattle, decreases of over 80% have been observed at optimum doses. The results of a study conducted on grazing beef cattle fed a pelleted

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seaweed supplement on a typical farm showed an average decrease of approximately 38 percent with no negative impacts on weight gain. The average reduction from the pooled estimate of available studies is around forty seven percent at typical doses of bromoform from seaweed, in line with the roughly fifty percent reduction that a few commercial developers of seaweed-based probiotics and supplements claim. The challenge of the science of the production of such an additive at scale. This seaweed needs to be grown either in the ocean or in tanks on land, harvested, stabilized and treated to ensure that its active ingredients are not destroyed during storage. Formulations include use of dried biomass, and steeping the seaweed in edible oils that are good at preserving bromoform, other approaches involve the use of synthetic analogues or completely different molecules that target the same enzyme. There is a range of results from different studies, which may be explained in part by the different behaviour of each formulation in the rumen. The common thread among them is that they are based on the same underlying principle a highly specific biochemical intervention, based on nature, to target a single microbial enzyme that contributes a major portion to global warming.

7. TECHNIQUES AND TECHNOLOGIES FOR MEASURING WHAT COWS ACTUALLY EMIT

The credibility of a methane reducing additive depends on the accuracy of the measurements and measuring the breath of a cow is not as straightforward as it first sounds. There are several complementary techniques which the scientific community has developed and an understanding of these can explain why there is a range of reductions reported in various studies. The most rigorous is the open circuit respiration chamber, a climate controlled chamber in which an animal is kept for days and all of the methane, carbon dioxide and hydrogen in each litre of air entering and leaving the chamber is analysed. Respiration chambers are highly accurate at capturing emissions including the small proportion from the hindgut and studies using them have the largest and most consistent reduction effects.

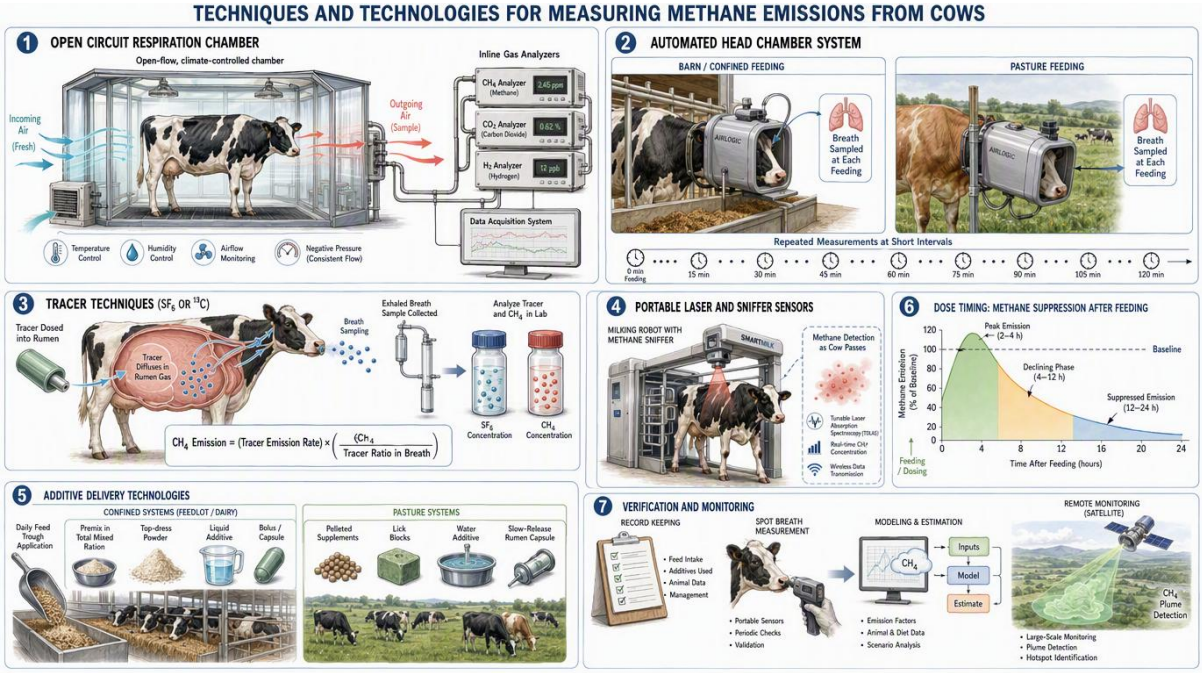

Fig -6: Techniques And Technologies for Measuring Methane Emissions From Cows

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The problem with them is that they are artificial animals are kept in, fed and deprived of their natural grazing patterns. Automated head chamber systems are used to measure emissions under commercial conditions feeding stations are placed in barns or pastures and a small ration of bait is fed to the animal, the sensor analyses the animal's breath every time the animal visits the feeding station. The short measurements can be repeated over weeks to provide a good emission profile for each individual animal without interfering with normal husbandry. It is this technology that was used in the grazing trials mentioned above. Other methods involve tracer techniques a harmless gas is released at a known rate from a device in the rumen and the amount of methane released can be calculated from breath samples and portable laser detectors and sniffer sensors that are attached to milking robots. In addition to measurement, the success of the delivery technology is crucial. Dairy and feedlot systems that are confined allow for a continuous and controlled application of additives in the daily ration. Systems on pasture are more difficult an animal on pasture cannot be dosed at each feed, so pelleted supplements, lick blocks, water trough formulations, and slow-release capsules which remain in the rumen and release active compounds over weeks or months have been developed. Dose timing is important because the active compounds are only active for a short period of time the methane suppression is greatest in the following few hours after eating, and diminishes as the compound breaks down. Lastly, technologies are coming to light to verify on farm reductions and link them to carbon markets. There are now standardised protocols to credit reductions of enteric CH_4 based on a mix of feed records, spot measurements and modelling. Satellite instruments that can identify methane plumes provide another level of independent monitoring at regional levels. These tools make an invisible gas auditable, the prerequisite for any tax, credit or premium system that is based on it.

8. WHAT RESEARCH ACTUALLY SHOWS VERIFIED RESULTS AND HONEST CAVEATS

It is often said that the evidence in the case of seaweed additives is so overwhelming that it can be boiled down to one telling number that is made public. That evidence needs to be unpacked, and both its strengths and its weaknesses need to be recognized, to be communicated responsibly. The strengths are very real. The 14 independent studies that were combined in a recent meta-analysis reported an average decrease in daily methane production of 47 percent, methane per kg of feed of 43 percent and methane per kg of milk or meat of 39 percent when using feed ingredients with bromoform.

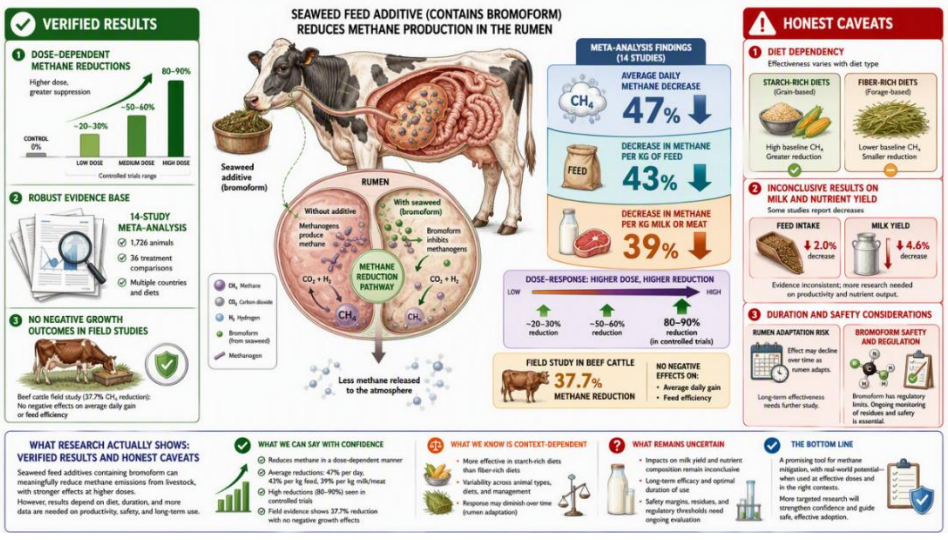

Fig -7: Seaweed Feed Additive

The higher doses resulted in greater decreases. In controlled trials, suppressions of eighty and ninety percent have been reported in individual trials. A field study of grazing beef cattle probably the most realistic study published to date showed an average reduction of 37.7 percent, but with no negative effects on growth. These are not side effects, few interventions in any economic sector can lead to a reduction of a major emission source by 50% in grams per day. The caveats should be given the same prominence. First, there are significant differences in the effects depending on diet they are more pronounced in the starch-rich feedlot diets, and less pronounced in the fibre rich forage diets, which are the most typical in the grazing and smallholder systems, which are most common in developing countries.

Second, evidence on the widespread claim that the additive enhances nutrient absorption and milk production is inconclusive. The meta-analysis revealed that feed intake was slightly reduced at the effective doses and milk yield of dairy cows was reduced by about 4.6 percent. There have been some individual studies of some of these related compounds that have demonstrated milk increases, and reduced methane does in principle save energy feed, but the productivity dividend is not proven. In one long test with high quality beef cattle, even persistently lower weight gains were reported. Yield claims should be viewed with skepticism by prospective buyers, until they have independent long-term data.

Thirdly, there are issues of duration and safety which need further investigation. Earlier methane inhibitors have proven to have a reduced effect over time due to adaptation of the rumen microbial community, it remains to be seen if seaweed additives will have the same effect over full lactation cycles and animal lifetime. Bromoform itself is a compound which is monitored by regulators, and although there have been published trials with no concerning residues in milk or meat when applied at the recommended rate, it is advisable to monitor this compound, and this is being done. All these caveats aside, technology holds great promise. They just set the honest limits between known and unknown or being learned and this is the article's intent to do the same.

9. THE ECONOMICS BEHIND THE ADDITIVE COSTS, INCENTIVES, AND RETURNS FOR FARMERS

There is no successful agricultural technology that is based on environmental merits alone. Farmers have little margin for error and anything that increases the costs but not the revenue will find it difficult to compete except in niche markets. So, the economic structure of methane reducing feed supplements should be carefully analysed as it will determine whether or not the science is realised in adoption on a meaningful scale. As the seaweed based additives are becoming more established in both cultivation and processing, the direct cost of the additives has significantly decreased. Now, developers in several countries are quoting a few hundred rupees 4-5 US dollars per cow per month, which are company estimates and vary according to the formulation, dose and market and which should be checked locally. Even this cost must be justified, for a smallholder with a low profit margin per animal. It is funded from four revenue streams. The first is carbon market. The methane reductions can be certified and sold as carbon credits to emission offsetting companies. Since methane is so effective, reducing emissions from one cow by half can equate to about a tonne of carbon dioxide equivalent per year, which is a significant credit value for the current price of the additive, and could even cover the cost of the additive.

The second is premiums in the supply-chain. Multinational dairy and food processors have pledged to cut their so called scope three emissions, the biggest proportion of which are on the farms that supply them. Some now co-pay for certified low methane milk or pay premiums for additives. Where emission taxes are

in place or are expected to be, the third is regulatory avoidance every kg of methane avoided is a kg of tax liability avoided.

The fourth improved feed efficiency and yield is still scientifically unproven and is not yet to be included in any business plan. The supply side of this economy is also noteworthy. The seaweed cultivation is evolving into an industry, providing jobs in coastal aquaculture, processing, logistics and verification services. Seaweed farming does not need any fresh water, arable land and fertilizer and can help to generate alternative income for fishing communities. Capital has been invested in cultivation projects on various continents, and IP, licensing models and competing formulations are quickly creating a true market. The opportunity is available across the entire value chain for countries with long coastlines and large cattle populations, from growing the seaweed, to feeding it, measuring and monetising the reduction. In short, the economics are no longer theoretical, but rather are being created contract-by-contract and farm-by-farm.

10. REGULATORY WINDS EMISSION TAXES AND THE CHANGING POLICY LANDSCAPE

Most of modern history has been characterised by agriculture being outside of climate regulation. That time is over and the loudest indicator is from northern Europe, where one country has introduced the world's first tax on GHG emissions from livestock. The deal between the government, farming organisations, trade unions and environmental groups means that farmers will pay a levy per tonne of carbon dioxide equivalent CO_2e emitted by their cattle and pigs from 2030 at the marginal rate equivalent to approximately forty US dollars per tonne, which will increase significantly from 2035. The base reduction rate will be sixty per cent for emissions which cannot be reduced now through known technologies and the income will be returned to the farming community to support green transition in that sector. It's a clever design for a tax that pays attention, in that it incentivizes precisely the technology this article describes.

The deduction is only for the unavoidable emissions, which means that if a farmer takes up a recognised methane reducing additive, immediately reduces the taxable base. The policy amounts to a financial instrument, however, because the environmental technology is transformed into a policy the additive is, in essence, a tax shield. The initial rates for unmitigated herds are estimated to be equivalent to one hundred US dollars or more per cow per year, changing the numbers of adoption. Other jurisdictions are following similar tracks, albeit with some choppy waters. One Pacific country has already implemented a similar pricing mechanism, which was abandoned after farmers protested and a change in government a reminder that agricultural climate policy is only effective when farmers are not the objects of it. The European Union is still considering how to include agriculture in emissions pricing schemes, and a number of countries have included feed additives in their official mitigation inventories and thus formally recognised them in their national climate accounting. Methane suppressing additives for commercial use are now approved in several key markets, which was a barrier to the technology up until now and limited its use to research stations. There's the gentle pressure of trade and finance. Dairy industries that export require their suppliers to have a carbon footprint, banks and insurers are increasingly considering climate exposure when lending to farmers, and over one hundred countries have made international commitments to reduce methane emissions by 30% by 2030, compared to 2020. Without that, livestock emissions are not exempted and it becomes unattainable. It's clear where the train is going from here through tax, credit, procurement or lending requirements, the price of unabated methane is going up and so is the value of proven methane mitigation.

11. THE OPPORTUNITY FOR NATIONS WITH LARGE CATTLE POPULATIONS

As methane mitigation is turning into a global market, the country with the largest natural stake in the market is the one with the largest number of cattle, and no country has more cattle than India. India has the largest bovine population in the world of about 193 million cattle and 110 million buffaloes over 300 million and is the largest producer of milk in the world, producing more than 230 million tonnes of milk annually. Livestock accounts for almost five per cent of national economic output and close to thirty per cent of agricultural output, and is the livelihood of an estimated hundred million rural households, the majority of which has less than ten animals. There are two sides to these numbers. They imply that enteric methane from the subcontinent is one of the biggest agricultural emission sources in the world, they also imply that no country would benefit more environmentally, economically and diplomatically from an affordable and locally produced solution. It is here that lies the strategic opportunity.

The additives developed in other countries are for intensive dairy and feedlot operations, and have been priced for affluent markets. The cost-efficient formulation, suitable for smallholder conditions, is not much built yet, which should be deliverable via cooperative feed systems, stable in tropical conditions, effective in fibre rich feed and affordable for smallholder farmers. The country which develops it will not only be able to provide for its own cattle, but for those of Africa, South-East Asia and Latin America, where similar conditions exist. India has a lot of resources to accomplish this. It has a more than seven thousand kilometers long coastline, which has a great potential for seaweed farming, and its government has already taken steps towards promoting seaweed farming as a livelihood for coastal communities. It has one of the most successful cooperative movements in the world in its dairy sector, which would offer a readymade channel for the simultaneous delivery of feed supplements, training and carbon credit revenues to millions of small farmers, few countries have such a distribution network. It has a long history of scientific research on ruminant nutrition and its pharmaceutical and aggrotech sectors have proven to be able to re-engineer costly technologies into low cost technologies for the world market. The award is not just about the emissions. Smallholder dairying could have an additional income stream from verified reductions and the income stream from carbon credits. There may be premiums for exporting dairy products with certified low footprints. Seaweed farming along the coasts can be utilized to utilize the fishing communities with falling catch. All of this will not happen on its own, but will take investment in research, regulatory certainty and patience in fieldwork in a variety of feeding systems. However, the right combination of need, size and capacity is uncommon and the countries that take the lead will set the tone for others.

12. ANIMAL WELFARE, FOOD SAFETY, AND ENVIRONMENTAL TRADE-OFFS THE OTHER SIDE OF THE LEDGER

However, the impact of any intervention that is given to hundreds of millions of animals every day should not just be measured in the emissions prevented it should also be measured in the impact on the animals themselves, the food they produce and the environments in which their raw material is grown. In each of these areas, the results of seaweed additives are promising but less than definitive, and it is important to be forthright about the issues. First, is animal health and welfare. Some of the animals in the published safety study on lactating dairy cows when fed the seaweed at target and above target levels were found to have abnormalities in the rumen wall with histological evidence of inflammation. Several trials have also indicated that cattle are reluctant to eat feed with the seaweed or actively sort out the seaweed, indicating palatability issues which may affect intake, which is also reduced slightly in pooled trials. In a long-term test with top quality beef cattle, there was always a weight gain penalty. None of these results render the

additive unsafe for use at the recommended dose, and other trials have yielded no adverse effects, but they do show that welfare outcomes are not to be taken for granted, but need to be monitored over entire production processes. Food safety is the second issue. Bromoform is a compound which regulators treat with caution. The good news is that the transfer studies have shown that bromoform does not bioaccumulate in animal tissues, it is present in milk only transiently and at levels close to background levels, which are well below the drinking water safety guidelines, and a comprehensive toxicological review in 2025 concluded that the risk to consumers is negligible as long as the intake does not exceed the degradation capacity of the rumen. Iodine is not so often talked about, but it is highly concentrated in seaweed, and an increased iodine concentration in milk is a separate residue problem, and needs to be monitored and controlled separately.

The third issue is that of the environment. Bromoform emitted to the air is an ozone relevant gas as well. A large-scale cultivation was proposed and the emissions from these farms were modelled in the atmosphere to find that the emissions from farms, which would be enough to provide feed for large sectors in the country, would be negligible for ozone depletion during normal operation. But systematic reviews warn that such scenarios, where supplies can be provided for a significant proportion of the world's herd, are poorly studied, and that as well as raising conventional aquaculture issues, nutrient dynamics, biosecurity and the ecological impacts of releasing intensive monoculture into coastal waters, would also be significant. None of the above points detracts from the argument presented elsewhere in this article. However, they do specify when deployment can be considered responsible when it is in a commercial rollout with welfare monitoring, when there is monitoring for both bromoform and iodine, when dose limits are based on the rumen's capacity to degrade, and when environmental assessment is done before cultivation is attempted on a large scale. The only way to gain public trust in a technology that claims to be a climate solution is to be held to the same standards of accountability as methane animal, consumer and coastline footprints.

13. WHAT SOCIETY GAINS NEW KNOWLEDGE AND ITS WIDER USEFULNESS

An awareness article is worth its salt if it leaves the reader with information he or she didn't previously have and demonstrates how that information can be valuable other than just for the sake of information. Many of the facts contained herein are probably new to most readers and each has social implications. The first is the position of livestock in the emissions hierarchy, that cattle as a group would be the world's third largest emitter. This is a new way of thinking about climate responsibility barn and pasture decisions are made in the same vein as those taken in boardrooms and ministries for energy. For citizens, this knowledge serves as a powerful tool to inform their food system, corporate food claims and public policy. It also prevents two extremes to minimize the impact of livestock emissions and to pin the responsibility of the issue on the farmer, who is in the process of being solved by science.

The second is the rectification of misconceptions of the people. The effectiveness of methane is time horizon dependent e.g. 80 times more potent than carbon dioxide over 20 years, 28-30 times more potent than carbon dioxide over 100 years and most of the methane is lost from the cow by belching rather than flatulence. Knowing these facts can help a public make a much more educated assessment of news articles and political statements and reduce alarmism and denial. The third is that there's a viable answer that doesn't involve a radical change in our eating habits, or giving up meat and dairy. Climate news is a list of sacrifices to many. But it's not the same with the seaweed story a natural compound, fed in gram quantities, can reduce a significant emission source by one half, without impacting farming families, food

traditions, or rural economies. If people are aware of such solutions, they can shift their public psychology from resignation to constructive demand that governments take additives into account when making policy, that dairy companies invest in adoption, and that research fills in the remaining pieces.

The fourth is the realization that in this field environmental and economic interests frequently depicted as opposing are coming together. Carbon credits, supply chain premiums and tax design are helping to line up the farmer's ledger with the planet's atmosphere. Those who understand can help drive the alignment by making informed purchases, can invest in the alignment, and young people can seek employment with sectors emerging around the alignment, such as aquaculture, animal science, and verification. Systems are more likely to be well understood by their members and more likely to make good collective decisions. To make the invisible chemistry of a cow's stomach visible and to demonstrate how this relates to climate, livelihoods and dinner tables – is exactly such an act of understanding.

14. THE GAPS THAT REMAIN IN PRESENT RESEARCH AND PRACTICE

Science communication should not just map what is known but also what is unknown, and there are many uncertainties around this technology that will have a tremendous impact on its future. The biggest scientific knowledge gap is that of long-term effectiveness and animal outcomes. Most of the published trials are only weeks or a few months in duration, commercial dairy animals have a lifespan of many years. It remains to be determined whether rumen microbial communities will adapt and recover from the impact of the inhibitors, as happened with some inhibitors in the past, and recover the methane production. Nor is the whole productivity picture what little evidence we have so far suggests that at effective doses, there are small reductions in feed intake and milk yield, which are not reflected in the marketing claims, and the theoretical energy saving from the reduced methanogenesis has not yet materialized as a measurable increase in milk or growth. Multi-year, full lactation studies in various breeds and climate are greatly needed.

The second gap is that between the location of the science and the location of the cattle. The great majority of trials are intensive systems in rich countries where the ration is made up of a high starch content, and where the additive is most effective. However, the majority of the world's cattle are kept in smallholder systems in Asia, Africa and Latin America where the effect measured is less pronounced and it is difficult to dose the cattle on a daily basis. Slow release capsules, water based formulations and lick blocks are delivery mechanisms that are immature for use with grazing animals. The buffaloes, which are present in more than two hundred million in the world and from which almost half of the milk production is obtained in some countries, are almost completely missing in the trial literature.

The third one is the gap in industry and economy. Even providing a small proportion of the world's herd would need the scale of seaweed farming which has never been achieved and processing techniques that could provide stability of the active compounds in tropical conditions at an affordable cost. Bromoform is volatile and has a tendency to deteriorate during storage quality control is an unsolved problem on a huge and decentralised supply chain. Carbon credit income systems that are affordable for smallholders, and without which income will not flow to the farmers that need it the most, are just starting to be developed. The fourth gap is regulatory and social. Approval regimes vary by jurisdiction and residue monitoring protocols are still in the process of being standardised, and the environmental impacts of very large scale seaweed farming on marine ecosystems should be studied with caution. Lastly, few studies consider the human aspects farmers' attitudes, adoption behaviour and extension strategies upon which all agricultural

technologies ultimately depend for success or failure. All of these gaps are also calls to action for researchers, entrepreneurs and policymakers, especially in the cattle-rich countries of the developing world, who are so conspicuously missing from the literature.

15. IMPLICATIONS FOR FUTURE GENERATIONS, FARMERS, AND THE DAIRY ECONOMY

Technologies are most important to those who will have to deal with them for the longest time and the impact of methane reducing feed additives is intergenerational, and spans the entire livestock value chain. The implications for future generations are based on methane's strange math. The gas has a lifetime of about 10 years, so emissions prevented today will lead to a measurable reduction in temperatures within the lifetime of today's school children, not over the next century as is the case for carbon dioxide reductions. Enterprise-wide mitigation of the enteric sector is thus one of the few options available to reduce near-term peak warming, while decarbonizing energy and industry. A generation that is handed a food system that is producing milk and meat at half the methane price is handed literally a cooler world than it would otherwise be.

The technology could alter the dynamic between smallholder farmers and dairy owners and their attitude to climate policy. They are no longer just emitters and potential taxpayers they are suppliers of an environmental service that can be verified. For a three-animal household that is part of a cooperative to link them to additive supply and carbon credit aggregation, climate action could come as a new revenue stream, rather than a burden, as buyers begin to impose footprint requirements. To achieve this vision, it is essential that cooperatives, governments and processors pick up the tab for transition and not pass the costs on to those who can least afford to pay, design decisions in the next decade will make the difference between the benefits being shared or captured. For corporate farmers, and big dairy businesses, the equation is economic.

Multinational processors with public emission reduction commitments are required to cut farm level methane or face being called out on the carpet for failure to do so, low methane milk is becoming a procurement category, and processors who act early will be considered preferred suppliers, enjoy premium pricing and be protected from future levies. In agribusiness as a whole, new sectors are being created, such as seaweed farming, formulation of additives, measurement of emissions, verification of credit, etc., with employment and export opportunities. The risks multiply for countries, particularly those like India where herds and dairy production are the world's largest and where leadership of a market is inevitable, irrespective of who is in charge. When the smallholder majority is addressed in terms of affordability and delivery, the scientists, farmers and entrepreneurs who have commercialised a supplement will not only have redefined the agriculture climate frontier for generations to come but will have done so for everyone.

16. CONCLUSION

The goal of this article was to let the public know, without embellishment, what's happening at the nexus of animal science and climate policy a quiet, but still significant, trend of the use of seaweed-based feed additives that can significantly lower methane emissions from cattle. The facts collected here lead to several definite conclusions, and warn of others. The fact that enteric methane from the world's roughly 1.5 billion cattle is one of the largest sources of near-term warming, is 80 times as effective as CO_2 at trapping heat over 20 years and that cattle as a group would be the third largest emitter is well established. It is also well proven by controlled trials and meta-analysis that the use of seaweed additives containing

bromoform can, at typical application rates, cut methane production by nearly 50% and by much more under optimised conditions and that regulatory action, such as the world's first livestock emissions tax which comes into effect in 2030, is turning methane reductions into economic value through taxes avoided, credits earned and premiums paid.

There is still no evidence that the additives have a positive effect on milk yield or animal productivity, if there is any effect, it is likely to be small and negative, and claims that they have a beneficial effect should be regarded as unproven. Nor is it known how the technology works over the entire life span of the animals, in grazing and smallholder systems, in buffaloes, or even at the industrial level of production that would be required for world-wide relevance. These gaps are not grounds for dismissing the research, but a blueprint of work to be done, and the cattle rich nations of the developing world are in the thick of it and have the least research going for them. The big picture lesson can be the best. Climate solutions frequently are presented as a battle between the environment and livelihoods, between science and tradition, between the rich consumers and poor producers. The seaweed in the cow ration offers a different perspective With a bit of clever biochemistry, some transparent measurement, and smart policy design, the interests of the atmosphere, the farmer, the processor and the consumer can all be aligned in one value chain. How well that alignment is achieved will depend on decisions in laboratories, ministries, cooperatives, and boardrooms made in this decade and involving the hundred million or so smallholder households that raise most of the world's cattle. The best way to assure that those decisions are made wisely for this generation and for generations to come is an informed public with a grasp of the promise and honest limitations of this technology.

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