methane

Review

Methane Advances: Trends and Summary from Selected Studies

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Abstract: The role of methane (CH_4) in the 21st century presents a critical dilemma. Its abundance and clean-burning nature make it a promising energy source, while its potent greenhouse effect threatens climate stability. Despite its potent greenhouse gas (GHG) nature, CH_4 remains a crucial energy resource. However, advancements in CH_4 capture, utilization, and emissions mitigation are rapidly evolving, necessitating a critical assessment of the advances, their potential, and challenges. This study aims to comprehensively evaluate the current state of the art in these advancements, particularly focusing on the emissions trends, with corresponding global warming potentials of projected CH_4 emissions, and a discussion on the advances that have been made towards reducing the impacts of CH_4 emissions. The areas of these advances include measurement, computational, numerical modeling, and simulation studies for CH_4, emerging technologies for CH_4 production, management and control, the nexus of CH_4 –X, and case study applications in countries. This study reports on these advances, which involves a technical review of studies, mainly from the last decade, discussing the technical feasibility, economic viability, and environmental impact of these advancements. Our trend analysis reveals that even though the share of CH_4 in the GHG mix has been around 19% compared with carbon dioxide (CO_2), still, CH_4 reduction would need to be highly subsidized because of the high global warming potential it has, compared with CO_2. We conclude that while significant progress has been made, further research and development are essential to optimize the performance, scalability, and affordability of these advancements. Additionally, robust policy frameworks and international collaborations are crucial to ensure widespread adoption and maximize the potential that comes with the advancements in the mitigation of the impact of CH_4 emission. This study contributes to the ongoing dialogue on balancing the potentials of CH_4 with its environmental footprint, paving the way for a future where this versatile resource can be utilized sustainably.

Keywords: methane; low-carbon emissions technology; sustainability; climate change; global warming potential

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1. Introduction

The exhaustion of fossil fuel reserves and the escalating environmental predicament from increasing greenhouse gas (GHG) emissions have catalyzed a notable upswing in scholarly investigations pertaining to clean energy and low-carbon technology and emissions removal and sequestration. Whatever the approach or technology adopted for the mitigation of GHG, the impact of each gas on global warming and climate change is very vital. Therefore, it is crucial to exercise moderation in every scenario to ensure that the resources needed and the act of elimination ultimately result in no controversy of unfavorable negative effects and the overall effect on global warming [1,2]. More predominantly, the focus for emissions mitigation for mitigating global warming has often been centered on carbon dioxide (CO_2), being the GHG with the highest global emissions at an average of 60% annually. Methane (CH_4) is the second most important (GHG) for climate change after CO_2 [3]. In fact, CH_4 has a higher capacity to store heat in the atmosphere than CO_2. Compared to CO_2, CH_4 remains in the atmosphere for a much shorter time (about 12 years compared to centuries for CO_2). However, it is a much more potent GHG that can absorb a greater amount of energy throughout its presence in the atmosphere [4]. CH_4 has a global warming potential that is 28 times greater than that of CO_2 on a 100-year scale and 84 times greater on a 20-year scale [5,6]. The International Energy Agency reports that from 2020 to 2021, CH_4 concentrations recorded the largest annual increase since records began. Real-time data indicate that CH_4 concentrations increased further in 2022. To ensure an optimal climate impact, CH_4 emissions over the entire life cycle of the natural gas used to generate electricity should be at most 3% of the total amount provided. If this threshold is exceeded, it would be more environmentally beneficial to use coal for power generation instead.

Reducing CH_4 emissions is crucial to achieving the climate targets set for 2050 [7]. When using natural gas for electricity generation, lifecycle CH_4 emissions must not exceed 3% of the delivered volumes because, in climate terms, it would then be better to use coal for electricity generation. Abating CH_4 emissions is, therefore, highly relevant to achieving the 2050 climate objectives [7]. The Scientific Advisory Council of the Climate and Clean Air Coalition (CCAC) states that a 50% reduction in CH_4 emissions from human activities over the next 30 years would result in a 0.2 °C reduction in the global temperature change. This reduction is an important measure to prevent the overall temperature increase from exceeding 2 °C [8]. Therefore, rising CH_4 concentrations in the atmosphere deserve special attention because of CH_4's significant potency as a GHG. It is necessary to intensify efforts to identify the various CH_4 origins and reduce its impact on global warming.

The Conference of Parties (COP) 28 represented a notable achievement in addressing CH_4 emissions, as many nations reached a consensus to shift away from reliance on fossil fuels. The "Global Stocktake" recommended implementing more significant reductions in emissions, particularly in CH_4, prior to 2030 to maintain the possibility of limiting the global temperature increase to 1.5 °C [9]. In line with the IPCC 6th synthesis report [10], the previous climate finance commitments between 2013 and 2021 [11] from advanced countries increased at COP 28, potentially bolstering initiatives to reduce CH_4 emissions in developing nations. Nevertheless, there are still obstacles to overcome, as there was no unanimous consensus on definite timelines and precise targets for reduction [9]. Executing these agreements is vital for achieving substantial reductions.

Significant progress has been made in the CH_4 fields in terms of measurement, mitigation, conversion, usage, storage, and other applicable end-uses, leading to the useful knowledge of the fundamental processes, applied techniques, and the interplay for timely, responsive, and supporting policy towards reducing the impact of CH_4 emissions.

This work begins with an introduction to CH_4 followed by a simple trend analysis of CH_4 growth history, and some projections are made based on CH_4 reduction scenarios to show the future values in terms of emissions and global warming potential (GWP). Further, the research advances towards CH_4 emissions mitigation are summarized from a collection of selected scholarly articles, as there is currently no exact consensus and regulation on CH_4 mitigation. The primary objective of presenting these contributions through our study is to deepen the comprehension of advancements in sustainable and low carbon energy solutions with CH_4. The study envisages also providing developments in CH_4 studies and recommendations in support towards developing a consensus regulation for CH_4 mitigation.

2. Trend Analysis in the Context of CH_4

CH_4, a potent GHG, has been steadily increasing since the pre-industrial era, with a record high observed within the last half-decade. This rise is primarily driven by anthropogenic sources such as fossil fuel production and use, agriculture, and land-based waste disposal [5]. The overall trend is upward, but emissions patterns differ by source. Emissions reduction has seen some positive results, but total emissions are still rising due to increased production. Figure 1 shows the emissions per GHG type with the differentiation of the contribution of CH_4 alongside other GHGs and the projected values by 2100.

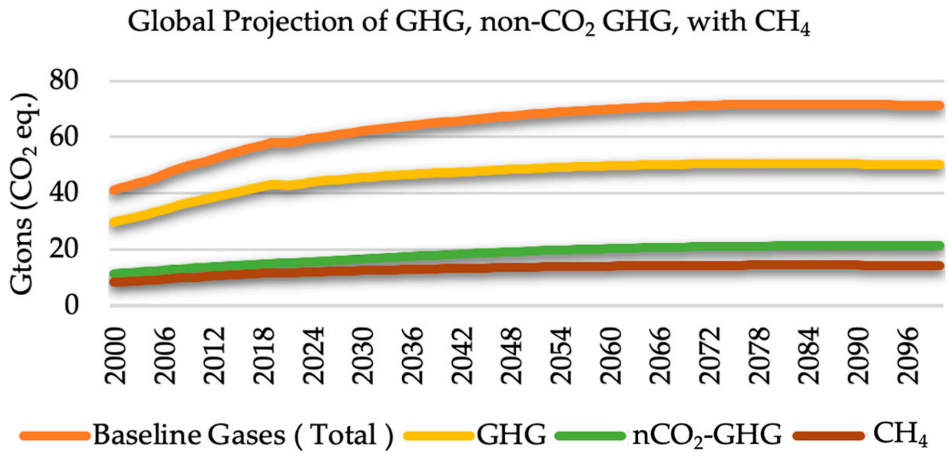

Figure 1. Global Projection of GHG, non-CO_2 GHG, with CH_4.

The projection of Figure 1 is based on the climate interactive EN-ROADS policy simulation forum [12], built on the concept of the aggregation of the system dynamics of socioeconomic factors such as population, historical trends of GHG emissions, economic growth (in this case, GDP), the global primary energy mix, and other factors forecasted based on the different literature sources.

The future projected CH_4 in Figure 1 was made on the assumption that the contribution of CH_4 to the overall GHG emissions would continuously be at an average of 19% of the total future baseline gases, given the past historical trends. Other non-CO_2 GHGs are expected to continuously have a smaller share in the overall total baseline gases. With these in mind, CH_4 contributions may reach a value of 12.42, 13.61, 14.25, and 14.26 Gtons CO_2 eq., in the years 2030, 2050, 2070, and 2100, respectively. Given the increasing rate of CH_4 emissions in the baseline (being business-as-usual), growing awareness of tackling CH_4 emissions is gaining worldwide recognition, leading to international initiatives and policy efforts. For instance, the just-concluded Conference of Parties (COP) 28 has strongly highlighted the dire need for CH_4 mitigation in support of several other proposals that have been long made in terms of reducing emissions from CH_4.

Despite the challenges, the projected values of future CH_4 emissions are instrumental to developing supporting policies to support the reduction of emissions from CH_4 as well as the consequential potency of different reduction scenarios, such as global warming and temperature change potentials. Hence, analyzing trends in CH_4 emissions in terms of GWPs and GTPs is crucial for understanding the present and future trajectory of global warming. While challenges remain in refining metrics and accounting for various factors, continuous research and improved understanding can inform effective climate mitigation strategies that address the unique role of CH_4 in a changing climate.

As effective emissions mitigation strategies involve reduction scenarios, Figure 2 leverages the emissions value of Figure 1 to present the projected values at different annual reduction levels consisting of 25, 50, and 75%, making the low subsidy, moderate, and high subsidy, respectively.

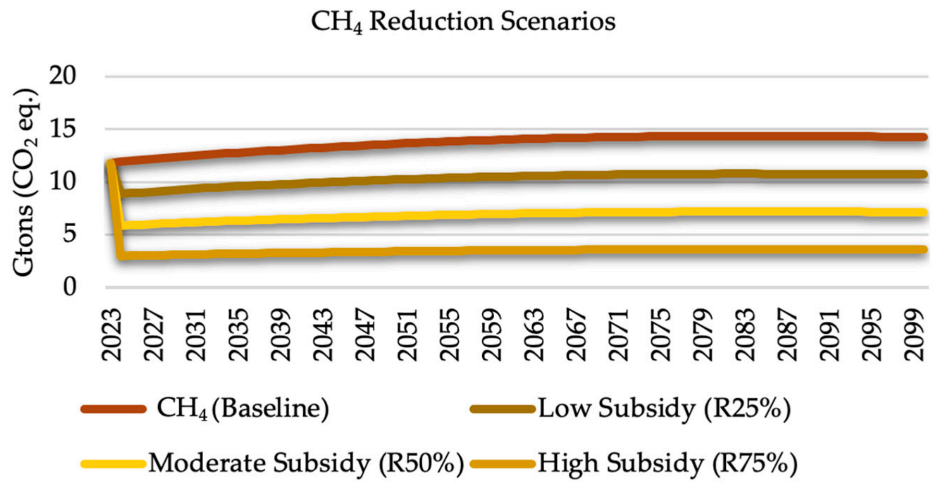

Figure 2. CH_4 Reduction Scenarios. (Note: 1st value across all scenarios is 11.79 Gtons CO_2 eq in 2023 and reduces in 2024 by 0, 25, 50, and 75% across the baseline, low, moderate, and high subsidies scenarios, respectively).

Upon obtaining the values of the reduction scenarios in Figure 2, the GWP is estimated for each of the scenarios in two-period intervals (20-year and 100-year, respectively). The (GWP), commonly used over a 100-year interval (GWP 100) based on the reference from the IPCC report [13], quantifies the proportional impact of greenhouse gases (GHGs) on global warming.

Hence, at GWP 100,

$$CH_4 \approx 28 \times CO_2 \quad (1)$$

while at GWP 20,

$$CH_4 \approx 84 \times CO_2 \quad (2)$$

Both the GWP 20 and GWP 100 values quantify the relative warming potential of a single molecule or unit mass of a GHG compared to CO_2 over a 20-year and 100-year time-frame, respectively. CO_2 equivalents (CO_2 eq) are estimated by aggregating these indicators to assess total GHG. The benefit of the GWP 20 is often tied to the short-term GWP that can be estimated since (CH_4) is short-lived, as compared to CO_2. Figures 3 and 4 show the GWP 20 and GWP 100 for the projected values of CH_4 across the four reduction scenarios.

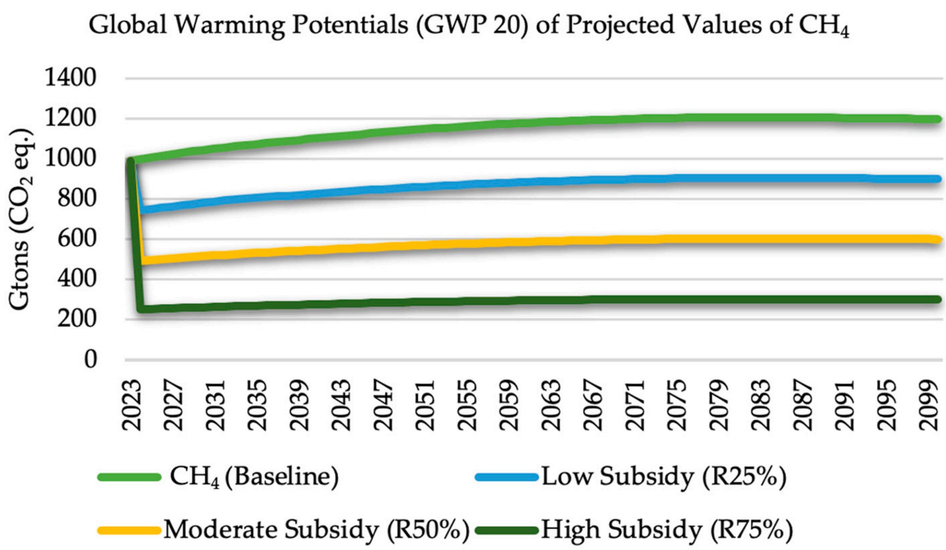

Figure 3. Global Warming Potentials (GWP 20) of Projected Values of GHG versus CH_4.

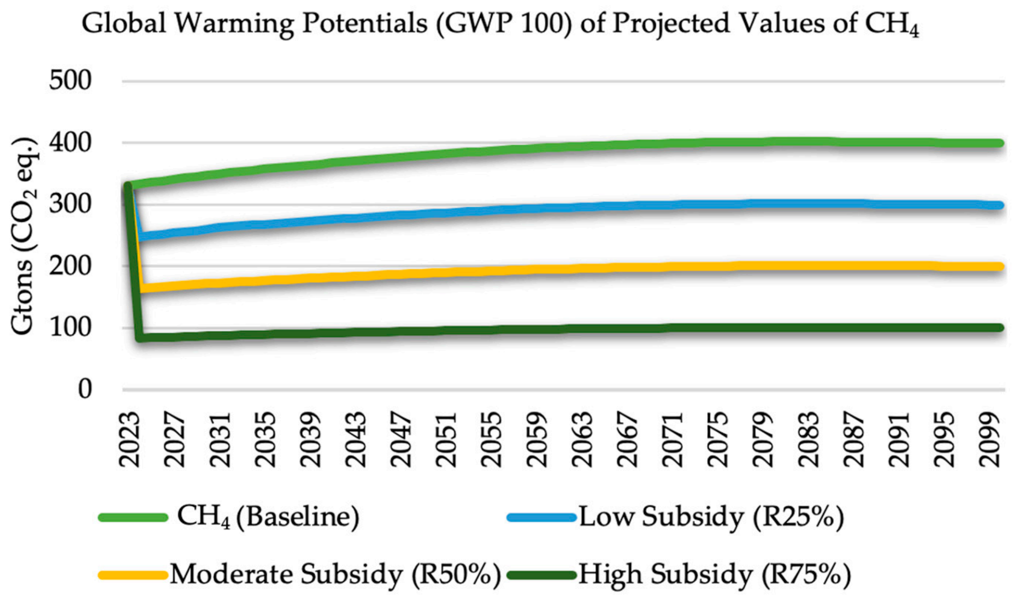

Figure 4. Global Warming Potentials (GWP100) of Projected Values of GHG versus CH_4.

The GWP 20 are quite higher compared with the GWP 100 values for CH_4, depicting the need for immediate mitigation actions and strategies that are compatible with the least possible consequent effect of atmospheric CH_4. Even the GWP 100 of the baseline reduction scenario is higher than the GWP20 of the high subsidy scenario. The GWP 100 of the actual projected CO_2 values of Figure 1 is compared with the GWP 100 of CH_4 and represented in Figure 5.

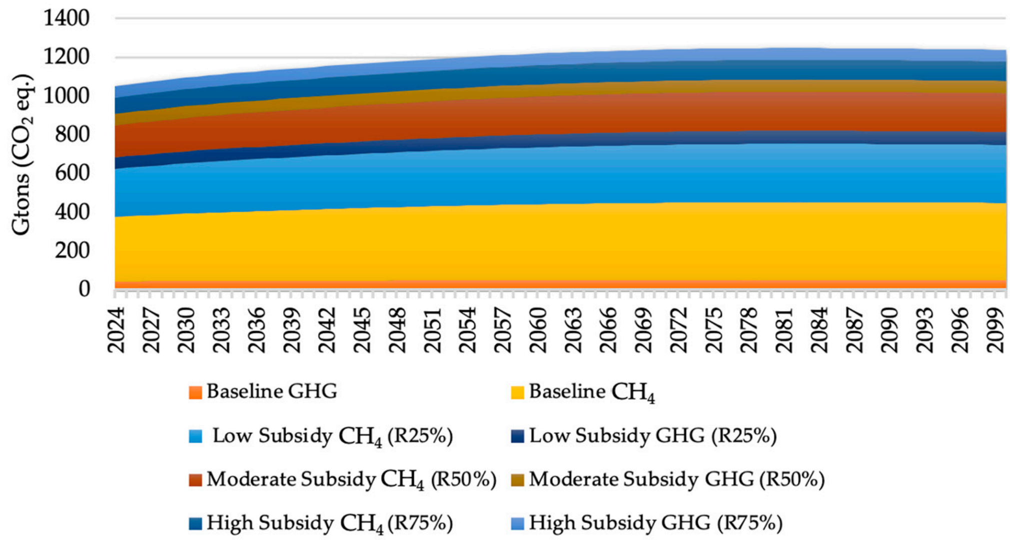

Figure 5. Comparison of Global Warming Potentials (GWP 100): GHG versus CH_4.

The high share of the GWP100 for CH_4 is seen in Figure 5, overshadowing the GWP 100 for the actual CO_2 across the baseline, low, and moderate subsidies, except for the high subsidy. Therefore, the urgent need to reduce CH_4 at a very high rate is very pertinent towards avoiding the effects of global warming.

Technological advancements offer promising solutions for achieving these reductions. Reducing CH_4 emissions can bring economic benefits through improved energy efficiency, waste management, and resource recovery. Addressing CH_4 emissions is crucial for mitigating climate change and ensuring a sustainable future.

The next sections present a summary of technological advances towards the reduction of the impact of CH_4.

3. Procedures for Summarization of Advances in CH_4

The collected work was summarized based on the procedures, as depicted in Figure 6.

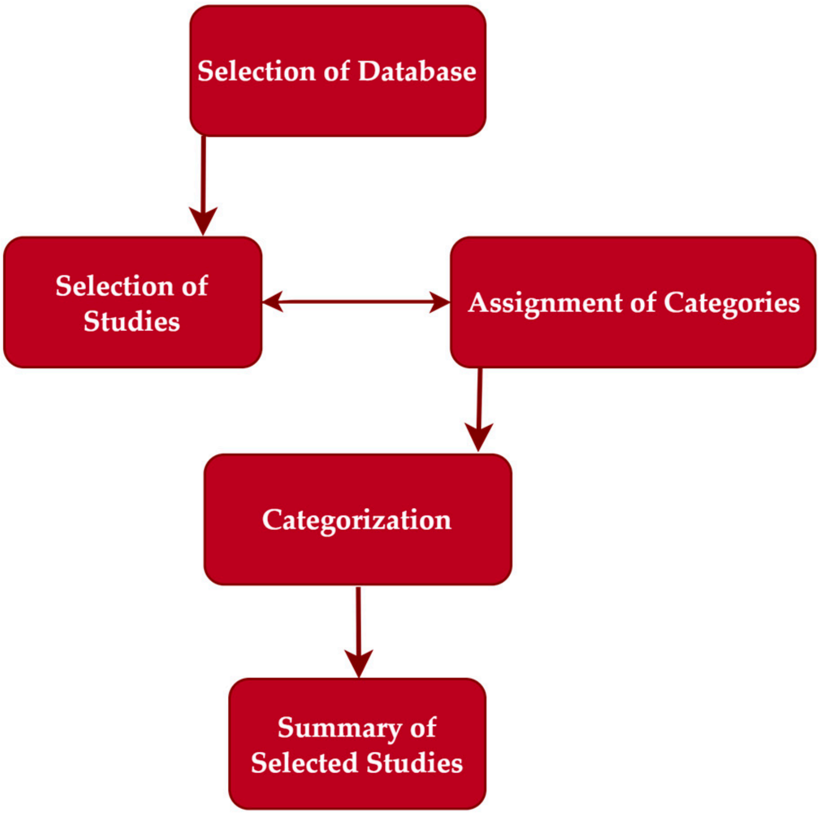

Figure 6. Procedures for Selection of Studies and Categorization.

The rationale behind the choice of this categorization is based on the context of the reviewed findings. This study explores various technologies and advancements reported in recent research on CH_4. Numerous research pertaining to CH_4 has been conducted and documented in various scholarly publications. However, it is noteworthy that none of these investigations have exclusively focused on the most relevant and comprehensive examination of CH_4-related phenomena. The focus of this study is a critical evaluation of scholarly articles dealing primarily with advances in CH_4. The papers in this work include both literature reviews and original research papers (experiments, models, and case studies) applied in seven different countries focusing exclusively on CH_4 studies. These contributions through our study deepen the comprehension of sustainable and clean energy solutions using CH_4, while guiding their advancement under the five categories, as shown in Figure 7.

Figure 7. Categories of the CH_4 Advances Summary.

4. Advances: Summary of Methods, Technologies, and Breakthroughs

Following the context of our research analysis, the findings are discussed subsequently.

4.1. CH_4 Measurement

There are currently numerous methods in the literature for measuring and estimating CH_4 emissions depending on the sector or applicable area. Knowledge of the advantages and disadvantages of each approach allows us to optimize experimental designs by considering the cost, appropriateness, and accessibility of methods for measuring and estimating CH_4 emissions. The choice of method should be based primarily on the purpose of the experiment; however, additional factors must also be considered. If a direct measurement of CH_4 is not possible, a reliable estimate can be obtained by using empirical or mechanistic models from the literature. In addition, there are several evolving techniques for quantifying and measuring CH_4 emissions. Each of these methods has its prons and cons, as shown in Table 1. It is important to note that no single method is suitable for the accurate monitoring of CH_4 emissions in all situations.

To reduce the time and cost of accurate and reliable CH_4 measurements using different technologies, as described in Table 1, supporting methods in the form of modeling are essential. The next section, therefore, discusses the progress made in CH_4 studies using computational, numerical, and simulation modeling.

Table 1. Major CH_4 Measurement Techniques.

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Energy Production							
Chamber method	The chamber method involves placing a closed chamber over the digestate storage tank and measuring the CH_4 concentration inside the chamber over time. The change in concentration is then used to calculate the CH_4 emission rate.	This method is suitable for measuring emissions from small and medium-sized digestate storage tanks. It is also a relatively simple and inexpensive method to implement.	It is relatively simple and inexpensive to implement. This method can provide accurate measurements of CH_4 emissions under controlled conditions.	It may not be representative of real-world conditions, as the chamber can create an artificial environment that does not reflect the actual temperature, wind, and mixing conditions of the storage tank. It can be time-consuming and labor-intensive to set up and operate.	The cost of the chamber method can vary depending on the size and complexity of the chamber, but it is generally less expensive than other methods, such as the open path method.	The accuracy of the chamber method can be good, but it is important to ensure that the chamber is properly sealed and that the measurements are taken under controlled conditions. The precision of the chamber method is also good, but it can be affected by factors such as the size of the chamber and the frequency of measurements.	[14–16]
Batch test	The batch test method involves taking a sample of digestate from the storage tank and measuring the CH_4 production rate in a sealed container under controlled conditions.	This method is suitable for measuring the potential CH_4 emissions from digestate.	It is less costly to implement and relatively simple to operate. It can provide useful information about the biodegradability of the digestate and the potential for CH_4 emissions.	It does not provide information about the actual emissions from the storage tank, as the test is conducted under controlled conditions that may not be representative of real-world conditions.	The cost of the batch test method is relatively low, as it only requires a few basic laboratory instruments.	The accuracy of the batch test method can be good, but it is important to ensure that the sample is representative of the digestate in the storage tank. The precision of the batch test method is also good, but it can be affected by factors such as the size of the sample and the frequency of measurements.	[14,17]
Open path method	The open path method involves using a laser or other optical instrument to measure the CH_4 concentration along a path between two points near the digestate storage tank.	This method is suitable for measuring emissions from large digestate storage tanks.	It can provide continuous measurements of CH_4 emissions over time.	It is more complex to implement than other methods. It can be affected by weather conditions and other factors that can interfere with the laser beam.	The cost of the open path method is more expensive than other methods, such as the chamber method or the batch test method, due to the need for specialized equipment.	The accuracy and precision of the open path method can be good, but it is important to ensure that the instrument is properly calibrated and that the measurements are taken under appropriate conditions.	[14]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Energy Production							
Downwind tracer flux measurement	This technique is used to estimate CH_4 emissions from natural gas production and use.	The method involves releasing a tracer gas, such as S_{F6}, into the atmosphere at a known location upwind of a source of CH_4 emissions. The tracer gas is then tracked downwind using a mobile laboratory equipped with a gas analyzer. By measuring the concentration of the tracer gas at different locations downwind of the source, it is possible to estimate the total amount of CH_4 emitted by the source.	It can be used to measure CH_4 emissions from a wide range of sources, including individual wells, compressor stations, and processing plants. It can provide estimates of emissions over large areas. It is relatively inexpensive.	It can be difficult to measure CH_4 emissions from sources that are located in complex terrain. It can be difficult to distinguish between CH_4 emissions from natural gas sources and other sources of CH_4, such as livestock.	The cost of the downwind tracer flux measurement method varies depending on the size and complexity of the project. However, it is generally considered to be a relatively inexpensive method.	The accuracy of this method can be affected by wind and speed. The precision of the downwind tracer flux measurement method is typically within 5%. Precision refers to the reproducibility of the measurements, while accuracy refers to the closeness of the measurements to the true value.	[18]
Laser CH_4 detector	It monitors long-term continuous CH_4 emissions at an oil and gas plants using a multi-open-path laser dispersion spectrometer, combined with Bayesian analysis algorithms using Monte Carlo Markov Chain (MCMC) inference	This methodology enables the identification, localization, and quantification of fugitive CH_4 emissions using the CH_4 path-averaged concentrations that are geographically distributed across the facility under study, in conjunction with the wind vector.	The capacity to measure a facility's overall emissions. Controlled, short gas emissions of 5 kg/h can beclearly detected and accurately measured.	Due to their low intensity, quantification of individual sources is difficult.	Still at developmental stage and total cost for actual implementation uncertain	Two distinct inference techniques could be used to establish a consistent estimate of a facility's overall CH_4 output.	[19–21]
Remote Sensing and Satellite Imaging	Satellites measure the amount of CH_4 in the atmosphere; typically, they do so by calculating the column-average dry mole fraction (XCH_4). This is converted into a flux via atmospheric inversion modeling42, from which emission sources can be located.	A spectrometer mounted on a satellite is used to measure the quantity of sunlight that is reflected off the Earth's surface. Depending on the gas, light from the sun is absorbed by the atmosphere and then reemitted at a different wavelength. The spectrometer scans the incoming light to identify the relevant wavelengths in the data—in this case, the CH_4-indicating wavelengths.	Possibility of application in developing emission profiles, tracking if emission targets are being reached, and long-term monitoring	There are location restrictions on their application, and the emission estimates they provide are highly uncertain.	Still at developmental stage and total cost for actual implementation uncertain.	Still at developmental stage and certainty of precision accuracy are yet to be fully ascertained.	[22–24]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Urban Environment							
Embedded sensor systems	It monitors the pollutant concentration and compares it with urban ambient environmental values	The integrated sensor systems are placed in weatherproof plastic casings with fans to suck outside air through the enclosure and over the sensor surfaces, with several air exchanges taking place per minute.	Quick identification of potential "hotspots" through sensor data, which could aid in resource allocation or early detection of potential air quality issues.	Due to their affordability and portability, they may be swiftly deployed over a range of geographical scales, especially tiny and localized ones.	It is important to calibrate and quantify sensors to satisfy the requirements of a particular environment and in response to the specific deployment circumstances, as they are likely to be extremely application dependent.	The accuracy and precision of the sensor data are minimal and can be mainly used as preliminary or supplementary data	[25]
Agriculture							
Sniffer technique	This technique includes the placement of components in automatic concentrate feeders, milking boxes, and milking parlors during milking.	During the milking process, gas samples are taken from the air in the feeding trough of an automatic milking system.	Performs hundreds of measurements in succession over long periods.	A greater coefficient of variation (CV) between animals compared to respiratory chambers (RC) or flux. In contrast to alternative methods (e.g., respiration chambers at 3000 L/min and the GreenFeed system for automatic emission monitoring (GF) at 1200 to 2250 L/min), this approach uses only the gas concentrations (typically achieved by passively pumping air to the sensor at 1.4 L/min) near the cow's muzzle.	Time-efficient and more cost-effective than the SF_6 tracer method.	Primarily offers the most accurate and precise measurement values for emissions. In scenarios where low CH_4 concentrations need to be evaluated reliably and with high accuracy, the amount of CH_4 lost increases with the CH_4 e emission concentration.	[26]
Lab-based (in vitro) incubation	Before analyzing gas samples for CH_4 concentrations, the feed substrate is incubated in airtight bottles or sacks to allow gas accumulation.	This method can initially be used to evaluate potential starting materials and additives in a controlled environment.	Time efficient and less costly compared to respiration chambers. It can be employed as a preliminary method for the evaluation of future feed ingredients and additives in regulated environments.	It could not accurately reflect the emissions of complete (in vivo) animals.	More cost-effective and time-efficient compared to respiration chambers.	This method may not reflect the emissions of the whole animal (in vivo).	[27,28]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Agriculture							
Sulfur hexafluoride (SF_6)	The concentrations of SF_6 and CH_4 are determined near the cow's mouth and nostrils using a small permeation tube containing SF_6, which is inserted into the rumen.	Enables motion for the animal. Affordable but more abundant in quantity; well suited for grazing systems. Instrumental method that can quantify significant numbers of individuals requires training.	Grazing systems are compatible with this feature, which allows animals to move freely. Ideal for handling large numbers of individual animals.	Extremely high risk of equipment failure and higher labor costs compared to ration chambers. CH_4 emissions from the hindgut are not measured. SF_6 is particularly potent and has a GWP value of 22,800. An additional difficulty is that SF_6 is a GHG.	Although they are cheaper, they require more ventilation and are more likely to fail.	Primarily offers less accurate and precise measurement values for emissions.	[29–32]
Open path laser	Beams of light are transmitted via wireless sensor networks and lasers across the pasture areas where the animals graze. The reflected light is analyzed for the concentration of GHGs.	Conducts assessments of CH_4 emissions from livestock and enables comprehensive measurements on several pastures on the farm. It is impossible to attribute emissions to a single source.	Measures CH_4 emissions from herds of animals and facilitates whole-farm measurements across a number of pastures.	It is costly. Depending on the environmental factors and the location of the test animals, sensitive measuring devices are required to analyze the CH_4 concentration.	Further monitoring of the equipment is necessary. It is costly. The analysis of CH_4 concentration and the collection of micrometeorological data require the use of sensitive instruments.	The location of the test animals and the environmental conditions have a considerable influence on the accuracy. The data must be screened thoroughly.	[33–36]
Open-circuit respiration chamber	As the animal is confined in a chamber, the CH_4 concentration in the exhaled air is measured.	Only a limited number of animals can be used for measurement at any given time. Unsuitable for investigating the effects of grazing management. The movement and normal behavior of the animals are hindered; feed intake may be reduced.	Emissions, including CH_4 produced during rumen and hindgut fermentation, are measured with extreme precision and accuracy.	Impractical to study the effects of grazing; it hinders the natural behavior and mobility of animals. Technically, its use is not mandatory. Both construction and maintenance are costly.	Both the construction and maintenance of buildings are expensive. Their use is technologically demanding.	Provides highly accurate and precise measurements of emissions, especially CH_4, from rumen and hindgut fermentation.	[37–41]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Agriculture							
Estimation from diet (models)	CH_4 is calculated based on the amount of feed consumed, using models often derived from previous experimental data.	Applicable in situations where measurements are not feasible. Requires estimates of feed intake which may be difficult to obtain.	Relevant in situations where measurements are not feasible. Effortless in predicting domestic or global emissions, they have a straightforward applicability.	Models are not suitable for investigating inter-individual variance in animals. Although there are numerous models for estimating CH_4 emissions from ruminants, most of them are based on feed intake data, which are difficult to collect on a large scale. Consequently, this limitation hinders their practical application. The use of experimental data for training limits the applicability of the models. The empirical models that have been developed focus primarily on the range of intake values within the data set used to generate the equations.	Once developed, it is inexpensive to use and makes CH_4 measurement unnecessary.	An accurate prediction of CH_4 production is complicated by the conditions and assumptions that each equation must satisfy.	[42]
Portable Accumulation Chambers	The animal is confined in a transparent polycarbonate cage for an estimated period of one hour; the measurement of CH_4 production is based on the increase in concentration that takes place during this time.	Tested on a sheep population. Intended for the genetic screening of a large number of animals for relative CH_4 production.	Developed to quantify a significant number of animals for genetic analysis of their proportional CH_4 emissions.	It is unclear whether they are comparable to respiratory chambers.	Comparable in price to open-circuit respiration chambers, but the measurement time is significantly shorter.	The degree of comparability with respiratory chambers is currently uncertain. Further research is required before allocating extensive resources to this method.	[43,44]
GreenFeed	A patented device is used to quantify and document the short-term (3–6 min) CH_4 emissions of individual cattle over 24 h. This procedure can be achieved by luring the animals to the device with a bait of pelleted concentrated feed.	Requires the use of an "attractant" to lure the animal into the plant and thus changes the results. Suitable for evaluating the effects of different meals or supplements.	Comparable to the respiratory chamber and SF_6 methods in terms of calculation accuracy.	Does not measure hindgut CH_4.	The device is patented and can only be obtained from the supplier, C-lock, Inc., based in Rapid City, South Dakota, USA.	Does not quantify CH_4 emissions from the hindgut. Results in similar estimates as the respiratory chamber and SF_4 techniques.	[45–47]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Agriculture							
Head Box System or Ventilated Hood Chamber	An airtight box surrounds the animal's head. Instead of measuring the gas exchange in the entire body, only the head is measured.	Prevents animals from moving and behaving normally, which is unsuitable for grazing systems. Can evaluate the emissions of different feedstuffs.	They are useful for obtaining continuous measurements over consecutive 24 h periods. In addition, this technique can be used to assess the nutritional value and energy metabolism of feed.	In this approach, the amount of CH_4 produced in the hindgut is not measured.	Training is necessary to familiarize the test animals with the hood device. Less expensive than a chamber that holds the entire animal.	It does not quantify the CH_4 in the hindgut.	[48–50]
Handheld laser CH_4 detector	It measures the amount of exhaled CH_4 in the air near the mouth or nose of an animal in a typical environment.	This method allows repeated CH_4 measurements in the same animal in its natural environment, whereas the sniffer and GF methods limit measurements to milking and feeding times.	A responsive, non-contact, non-invasive method that enables real-time assessment. On commercial farms, the handheld laser is easy to operate.	Influenced by variables like humidity, air pressure, temperature, wind speed, and the proximity of other animals.	Less expensive and easy to operate.	Humidity, temperature, and wind velocity (particularly important for pasture conditions) are environmental variables that can influence the accuracy of measurements.	[51]
Landfills							
Micrometerological	This method measures CH_4 emissions using towers equipped with fast-response CH_4 sensors and wind speed and direction sensors. These measurements are then combined with atmospheric transport models to estimate emissions.	This method can be employed to quantify all gas emissions entering and exiting a specific volume of air surrounding the source. The emission rate is determined by subtracting the output flux from the input flux.	It measures the absorption of CH_4 from the atmosphere, often referred to as negative emissions. Performs continuous measurements over some time to capture the temporal patterns of emissions. This method quantifies with precision the total CH_4 emissions emanating from specific sources or small open areas.	It is not suitable for a CH_4 mitigation study. Measuring the variability of emissions can be challenging when considering the relationship between the footprint of the technology and the total source area, especially when the ratio is very small. This method can lead to either over- or underestimating emissions.	This method is usually expensive.	The measurement of CH_4 is influenced by the surrounding weather conditions, such as wind speed and landscape, resulting in variations in accuracy and precision.	[52]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Landfills							
Aircraft mass balance	A common strategy for this technique is to fly circular trajectories at different altitudes around a source, continuously measuring CH_4 concentrations, wind speed, and wind direction.	This technique can be employed to estimate the amount of emissions from specific facilities such as an animal feeding operation, a landfill, or a natural gas processing plant.	Simplified flow-through models and sophisticated inversion models are employed for the analysis. Vertical profiles of CH_4 concentrations can be obtained by searching for specific emission sources.	The process of quantifying the spatial and temporal variations in emissions is labor-intensive.	Costly to utilize.	This method can detect emissions only when they are encountered at the specific altitude and radial distance of the flight.	[53]
Wetlands							
Dynamic chamber (DC)	The system quantifies the inflow and outflow of air as well as the concentration of certain gases in the air. It also monitors the initial and final concentration of gases in the chamber.	The chamber approach has been applied in various contexts, including quantification of emissions from landfills and via pipelines, water surfaces (using floating chambers) in lagoons for manure management, small groups of animals, and individual or small groups of animals.	Surface measurement chambers usually have an area of no more than 1 m^2 and are valuable for quantifying emission variations.	They are a labor-intensive process that can be partially mitigated using automated chamber systems and special chambers with a volume of more than 1 m^3.	They are costly and labor-intensive in terms of requirements for maintenance and power supply.	Measurement of high frequency with minimal disturbance DC is more likely to detect actual CH_4 emissions from the aquatic environment.	[53]
Generic							
Enclosure (chambers) technique	The emissions of a limited area (or a population of animals) are quantified directly.	This method can be used to precisely measure the emissions of small groups of animals or industrial activities in a controlled environment.	Quantifies the rates at which atmospheric CH_4 is oxidized in the soil, especially "negative" emissions caused by significant soil oxidation capacities. Relies on atmospheric modeling to calculate fluxes independently. Determines the rates of diffusive emission from a small source area (usually 1 m^2 or less) under day and night conditions.	Single enclosures may not be able to capture the full variability of emissions. Measuring the variability of emissions in extensive source areas is a labor-intensive process that requires the use of geostatistical techniques, a considerable number of chamber measurements, and additional data. An instantaneous measurement is obtained, which needs to be repeated to capture temporal trends.	They require higher financial investment and maintenance costs.	CH_4 emissions in the range from 1.02 to 512 g h^{-1} can be quantified with an accuracy of +14/−14%. Accurate measurements can be made for emissions from single animals or small groups of animals kept in a controlled environment.	[14,18,52,53]

Table 1. *Cont.*

Sector/Technique	Description	Application	Pros	Cons	Cost	Accuracy and Precision	Refs.
Generic							
UAV with Laser detectors	An airborne laser absorption spectroscopy, performed using portable CH_4 detectors mounted on board UAV	The methods comprise integrating an unmanned aerial remote sensing complex with the Laser CH_4. This complex is built around a multirotor unmanned aerial vehicle (UAV) with a Pixhawk flying controller, built on the Arduino platform.	The integration method adopts a more rational approach by giving the UAV flight controller the main responsibility for gathering and processing data. This removes the need for alternative hard-to-replicate technologies, highly sophisticated serial CH_4 detectors, and the necessity to install extra devices (such as smartphones, GNSS sensors) on board the UAV.	The technology is still at infancy and may not be applicable for situations with no laser detector employment for CH_4 emissions measurement.	The cost appears relatively low. However, the applicability of these technology to CH_4 measurement across many sectors is needed to ascertain it actual cost implication.	The accuracy of result obtained is constrained by the precision of the laser sensor.	[54]

4.2. Computational and Numerical Modeling and Simulation Studies for CH_4

To obtain accurate and reliable measurements of CH_4 using different technologies, it is crucial to develop a model based on data derived from potential sources of GHGs. These models can be developed using numerical simulations, which establish a relationship between the exhaust emissions of the sources and the observations of GHG concentrations. Therefore, the use of numerical modeling and simulation in these processes is critical to understanding the impact of engineering design on efficiency and cost. Therefore, these methods can be employed to identify and evaluate potential areas of improvement in emerging and prospective CH_4 measurement technologies. Based on optimizing feeding composition and the C/N ratio, Wang et al. [55] employed a mixture of dairy manure (DM), chicken manure (CM) and wheat straw (WS) for improving CH_4 yield from anaerobic digestion of multi-component substrates. Maximum CH_4 potential was achieved with DM/CM of 40.3:59.7 and a C/N ratio of 27.2:1 after optimization using response surface methodology. Co-digestion of DM, CM and WS performed better in CH_4 potential than individual digestion. A larger synergetic effect in co-digestion of DM, CM and WS was found than in mixtures of single manures with WS. As the C/N ratio increased, CH_4 potential initially increased and then declined. C/N ratios of 25:1 and 30:1 had better digestion performance with stable pH and low concentrations of total ammonium nitrogen and free ammonia (NH_3). According to the study, better performance of anaerobic co-digestion can be fulfilled by optimizing feeding composition and the C/N ratio.

Frerichs and Eilts [56], used a predictive combustion model in implementing a GT-Power. The results showed that the onset of combustion and the combustion parameters can be accurately predicted over a wide range of injection times and operating conditions. In addition, the study provided a detailed representation of the different combustion stages and the conventional NOx model that adequately represents the effects of injection timing on NOx emissions.

Muradov et al. [57] investigated a novel technological approach for the environmentally friendly production of H_2 from natural gas by catalytic autothermal pyrolysis of CH_4. In this study, carbon-based catalysts were used because they are available, durable, inexpensive, and resistant to sulphur and temperature. The thermodynamic analysis of CH_4 decomposition was performed using the AspenPlusTM chemical process simulator. Experiments were also conducted to verify the feasibility of autothermal catalytic pyrolysis of CH_4 over carbon-based catalysts at a wide range of temperatures and O_2/CH_4 ratios. The study demonstrates the feasibility of using carbon-based catalysts for the autothermal catalytic pyrolysis of CH_4. This method has the potential to produce H_2 with significantly lower CO_2 emissions than conventional methods such as SMR. This study recommends further research and development to optimize the autothermal catalytic pyrolysis process.

In 2023, Alvarez-Borges et al. [58] looked at three different U-Net segmentation methods (AI models) to separate XCT images of sand that contained CH_4 that had different levels of contrast. This used artificial intelligence training and modeling. The use of a small number of training images reduced the operator's time to train each U-Net model. Also, the U-Net models that were used—the 3D hierarchical, the 2D multi-label and multi-axis, and RootPainter—are new for this CH_4-bearing sand application, but they can all be used in a lot of different situations. The segmentation accuracy of the models is higher than that of mainstream watershed and thresholding techniques. It is recommended in this study that the industrial applicability due to the short period to train larger data sets should be adopted for further studies.

Cavalcante et al. [59] studied the auto-thermal reforming of CH_4 via thermodynamics analysis vis-à-vis the effect of pure oxygen or air as an oxidizer, using Gibbs free energy minimization and entropy maximization methods. Simulations were carried out using General Algebraic Modeling Systems (GAMS®) 23.9.5 software and thermodynamic analysis was carried out using CONOPY3 Solver. It was concluded that the use of air as an oxidizer produced a high yield of the compound of interest as compared to the use of pure oxygen. Table 2 summarizes the modeling and simulation parameters used in the selected studies for CH_4.

Table 2. Comparative analysis of modeling and simulation parameters used in the selected studies for CH_4.

Source	Methodology	Operating Conditions	Model	Material Used	Obtained Results	Suitability	Limitation
Wang et al. [55]	RSM analysis	DM/CM of 40.3:59.7 C/N ratio of 27.2:1	n/a	Dairy manure (DM), chicken manure (CM) and wheat straw (WS)	The study found that the optimal C/N ratio for co-digestion was 27.2:1, and the optimal feeding composition was DM/CM of 40.3:59.7.	These results suggest that optimizing feeding composition and C/N ratio can improve the performance of anaerobic co-digestion.	n/a
Frerichs and Eilts [56]	Predictive combustion model	n/a	Standard Extended Zeldovich Mechanism	GT power	Prediction with an accuracy of approx. ±2 °CA for different charge air temperatures and different air–fuel ratios at one operation point with 450 1/min and 9.1 bar BMEP	It can be used to predict unburned fuel and thus improves the prediction of brake-specific fuel consumption (BSFC).	Calibration of the models using measurement data from a single-cylinder engine is time consuming.
Mitoura dos Santos Junior et al. [57]	Thermodynamic	CH_4/H_2 ratio 1:10 at 1600 K and 50 bar	Convex nonlinear programming (CONOPT) model	GAMS software using the CONOPT 3 solver	CH_4 conversion = 94.712%	It is suitable for the CH_4 thermal process, incorporating thermodynamic modeling of Gibbs energy, thereby avoiding the formation of solid carbon in the heating system.	The amount of solid carbon is another barrier to its application, as the solid carbon formed is deposited in the equipment, causing clogging in addition to deactivating the catalysts.
Alvarez-Borges et al. [58]	(i) A bespoke 3D hierarchical method, (ii) a 2D multi-label, multi-axis method, and (ii) RootPainter, a 2D U-Net application with interactive corrections	Hydration time—30 h Temp—2 °C Pressure—10 MPa	U-Nets (Convolutional Neural Network Model)	Custom rig	It was found that the segmentation accuracy of all three methods surpassed mainstream watershed and thresholding techniques.	The study demonstrated that the U-Net methods used were suitable for accurately identifying the CH_4 gas phase using a small number of training images.	However, it is often time consuming, with its computing being resource-intensive, operator-dependent, and tailored for each XCT dataset due to differences in greyscale contrast.
Cavalcante et al. [59]	Gibbs energy minimization and entropy maximization methods	1 to 10 atm 873 and 1073 K steam/CH_4 ratio was varied in the range of 1.0/1.0 and 2.0/1.0 oxygen/CH_4 ratios in the feed stream, in the range of 0.5/1.0 to 2.0/1.0	Thermodynamic model: virial equation of state (EoS)	The software GAMS® 23.9 and the CONOPT3 solver	The mean reductions with increasing temperature in the percentage increase of H_2 and syngas using air under 1.5 and 10 atm, at the different O_2/CH_4 ratios, were 5.3%, 13.8%, and 16.5%, respectively.	This study is suitable for the auto thermal reforming of CH_4 using atmospheric air as an oxidizing agent to increase the production of hydrogen and synthesis gas.	The ideality of the gas phase is a factor that brings a certain limitation to the analyses conducted and consequently affects the range of application of the results obtained.

4.3. Emerging Technologies for CH_4 Production, Management, and Control

The development of new technologies for the production, management, and control of CH_4 is essential in addressing environmental issues, enhancing measurement and energy efficiency, and reducing the impact of CH_4, a powerful GHG. Emerging technologies for CH_4 production in this section discuss improvements in established procedures such as anaerobic digestion, fermentation, biomass gasification, and pyrolysis. Furthermore, discussions on the management and control of CH_4 technologies also highlight progress in mitigating indiscriminate CH_4 emissions from livestock (enteric CH_4), detecting CH_4 leakages in pipelines and natural gas fields, improving CH_4 utilization, and efficient CH_4 storage. These recent technologies, as discussed in this section, have promising potential to ensure the efficient production and utilization of CH_4.

4.3.1. Increasing CH_4 Measurement Efficiency Production and Conversion Rate

a. Improving Measurement from Ruminants

Given the significant contribution of ruminants to CH_4 emissions, already discussed in Section 3 alongside other sectors, the need for accurate measurements in this sector is growing as awareness of the link between CH_4 emissions and climate change increases. While traditional approaches exist, they are not without flaws. Fortunately, new technologies are emerging that could improve our understanding and mitigation efforts. Table 3 provides an overview of some of these approaches.

Table 3. Pros and cons of various emerging methods for measuring and estimating CH_4 emissions from ruminants [60].

Emerging Methods	Pros	Cons
Polytunnel	Suitable for quantifying CH_4 emissions from a small herd of grazing animals. This device is very portable and easy to use.	Regulating the temperature and humidity in the tunnel is a major challenge.
CO_2 as a tracer gas	It can easily be used on a wide range of animal species.	It is subject to major fluctuations from day to day, which makes it unsuitable for precise measurements. CH_4 emissions from efficient cows were overestimated, while those from ineffective cows were underestimated.
Intraruminal Telemetry	Perfect for collecting and analyzing data in real-time.	The electronic circuit of an electrical device is subject to corrosion in the rumen due to the harsh rumen environment.
Infrared Thermography	Straightforward method requiring no intrusion or invasion and is comparatively affordable.	No correlation has been observed between the temperature of a particular body region and the emission of CH_4.
Blood CH_4 Concentration tracer	The ability to quantify a large number of animals.	A disruptive technique used when taking a blood sample. The approach provides only a limited representation of CH_4 concentration.

b. Organic Biowaste

Alino et al. [61] evaluated the efficiency of an inexpensive, alternative, and more sustainable method to improve the biodegradability of Sugarcane bagasse (SCB) and increase CH_4 production by pre-storing it with acidic organic biowastes, such as cheese whey (CW) and fruit and vegetable waste (FVW). CW and FVW are lactic acid and acetic acid acidogenic [62], especially during the fermentation step, which ensures the acid hydrolysis lignin barrier in the SCB, granting microbes access to the cellulose and hemicellulose components for acidogenesis, acetogenesis, and eventually methanogenesis [63]. Furthermore, their rich organic matter composition of FVW and CW ensured sufficient microbes available for the steps mentioned above. This study showed that the pre-storage of SBC with FVW proved to be the best strategy to increase CH_4 production from SCB while simultaneously avoiding the use of chemical reagents that result in toxic effluents. It is suggested that future studies should focus on the determination of the lignocellulose content of the solid fraction after the pre-treatments to evaluate the cellulose degradation promoted by them.

Gborbani et al. [64] investigated the use of ozonolysis pretreatment to enhance the delignification of wheat straw. The effects of five factors on the delignification process were studied using response surface methodology (RSM). These factors were: ozone production rate, reaction time, flow rate of ozone/oxygen, moisture content, and urea content. Wheat straw samples were treated with ozone under different conditions, and the degree of delignification was measured. The study found that ozonolysis pretreatment was an effective method for delignifying wheat straw. The highest level of delignification (50%) was achieved using a combination of high ozone production rate, long reaction time, high flow rate of ozone/oxygen, low moisture content, and high urea content. The study recommends that further research be conducted to optimize the ozonolysis pretreatment process for different types of lignocellulosic biomass.

Dey et al. [65] investigated the effects of garlic oil supplementation on enteric CH_4 production in buffaloes using an in vitro rumen fermentation system. In this study, four concentrations of garlic oil (0, 33.33 μL/l, 83.33 μL/l and 166.66 μL/l buffered rumen fluid) were added to the fermentation medium. The study measured gas production, CH_4 concentration, rumen fermentation parameters and ruminal enzyme activity. It was found that the addition of garlic oil at a low dose (33.33 μL/l rumen fluid) reduced enteric CH_4 production of the buffaloes in the intestine without affecting the digestibility of the feed. This result suggests that the supplementation of garlic oil could be a possible strategy to reduce CH_4 emissions from ruminants without compromising animal productivity.

Baffa et al. [66] investigated the associative effect of changes in the proportions of feed ingredients and the chemical composition of ruminant diets on in vitro gas production. They used a randomized 3×10 factorial arrangement of 3 forages. Assays were prepared by the method of AOAC and made use of R-software (R Foundation for Statistical Computing, Vienna, Austria) for the analysis. Based on their analysis, it was shown that the associative effects on in vitro gas production were high in the first 12 h of incubation. Still, the extent varies with the solubility of the carbohydrate content of the forage in the diet.

c. Pyrolysis with Hydrogen Addition

Wnukowski, Gerber, and Mróz [67] presented an investigation of the impact of a hydrogen addition on CH_4 pyrolysis in microwave plasma, with the main focus given to C_2 compounds and soot products rather than hydrogen. For this ratio, a significant improvement in the CH_4 conversion rate was observed (from 72% to 95%) along with the increase in the acetylene (C_2H_2) and ethylene (C_2H_4) yield and selectivity, which are valuable products that can be used in various industrial applications. Acetylene is often used in welding and cutting, while ethylene is an important basic substance in the production of polyethylene, a widely used type of plastic [68]. The authors hypothesize that the hydrogen radicals present in the plasma enhance the conversion of CH_4, while the presence of molecular hydrogen changes the distribution of products towards C_2 compounds. Eliminating solid carbon enabled the shift in product distribution, which decreased solid carbon production as a result of the rise in C_2 compounds [69].

Moreover, the addition of hydrogen resulted in the formation of larger carbon particles. When both nitrogen and hydrogen were added, the formation of carbon was completely inhibited, and hydrogen cyanide became the main product formed instead of soot and some acetylene. However, the flammability of hydrogen in the presence of air and its relatively low ignition energy makes it necessary to take various precautions when carrying out this experiment on an industrial scale. When dealing with pyrolysis temperatures, it is essential to use gas leak detection and ventilation technologies, explosion protection measures, hydrogen inventory limits, and compliance with national and international regulations.

d. Evogen Microbial Additive

Sfetsas et al. [70] investigated the effect of Evogen microbial addiction on biogas production and digester status with a view to improving the performance efficiency of biogas production systems. The authors examined the Evogen microbial biogas additive on two different biogas plants and performed RNA sequencing. The study found that the addition of the Evogen microbial additive resulted in distinct shifts in the microbial community within the biogas plants. There was an increased abundance of methanogenic archaea and hydrolytic bacteria, which are key players in the anaerobic digestion process, hence significantly improving the biogas production and process stability, as indicated by the volatile fatty acids' (VFAs) profiling. These shifts in the microbial community were associated with an improved digester performance, as evidenced by the higher alkalinity buffer capacity (FOS/TAC ratios). This buffer capacity indicates enhanced acidification and methanogenesis, along with reductions in the total solids and volatile solids, demonstrating improved organic matter degradation. It was suggested that RNA sequencing could be used to examine enzyme changes for a deeper understanding of the impacts of Evogen on anaerobic digestion processes.

Notwithstanding the success of BG01 and BG02, the feasibility of scaling up this method depends on the cost of the additive, the ease of implementation, and the uniformity of results for different feedstock types and operating conditions [71]. Maintaining a stable microbial community is essential to achieve optimal and consistent biogas yields. Therefore, additives such as Evogen can change the composition and movement of the microbial community. This can cause changes in how substrates are used, metabolic interactions, and the structure of the community. Although this additive has the potential to improve biogas production, it could also complicate the management of the microbial community and the maintenance of process stability. In addition, only a limited number of recognized microorganisms can be cultivated for various reasons, such as a lack of certain nutrients, oxygen levels, temperature, pH, biological interactions, and a lack of growth factors [72]. This makes it difficult to regulate and predict the behavior of the microbial community in biogas plants.

e. Specific Additives under high pH and NH_4 Concentration

Economou et al. [73] studied the effects of using zeolites and trace elements on three biogas production plants (BG01–BG03) operating under high concentrations of ammonia and pH. Zeolite was added to the BG01 and BG03 plants for two months, contributing to the reduction in the total ammoniacal nitrogen values, which helped in reducing ammonia toxicity. Also, physiochemical characterization discovered trace element concentrations, which could limit microbial activity. Hence, 5 kg of a trace element mixture, such as iron, cobalt, nickel, selenium, etc., was added to the BG02 plant every week for 60 days to supplement the low concentrations discovered in the BG02 plant. It was observed that the use of specific additives stabilized the pH and reduced ammonia toxicity in the plants. They recommended diagnosing the problem of instability of anaerobic degradation so that appropriate additives could be used for corrections. Since the effects of these additives are often plant-specific, existing biogas plants could, hence, benefit from these additives by assessing the feedstock type and quality, plant performance, and the specific challenges being faced (such as low biogas yield, process instability, or high ammonia levels). This assessment would help in selecting the appropriate additives, such as trace elements mixtures, pH stabilizers, anti-foaming agents, or specific microbial cultures. Final monitoring and adjustment would help ensure optimal biogas yields.

f. Enteric CH_4 Reduction Management

Esen, Palangi, and Esen [74] reviewed current genetic and nutrigenomic approaches to reducing enteric CH_4 production without posing any danger to animals or the environment. The authors discussed two major approaches to reducing enteric CH_4 emissions: manipulating ruminants via the genetic selection and manipulation of the rumen microbiome. In genetic selection, animals with a higher genetic merit through next-generation sequencing are selected. The goal is to permanently and cumulatively reduce the amount of CH_4 produced per unit of milk or meat through genetic selection. This approach is based on the understanding that a genetic component to the amount of CH_4 an animal produces exists. Hence, animals that produce less CH_4 can be selected for breeding. The second approach, which involves the manipulation of the rumen microbiome, involves altering the microbial population in the rumen, the first stomach of ruminants where CH_4 is produced. Targeting specific groups of methanogens could reduce CH_4 emissions by changing the animals' diet, the use of feed additives, such as 3-nitrooxypropanol (3-NOP), canola oil, soybean, or linseed oil, in certain percentages, and introducing specific microbial strains such as *Prevotella* and *Dialister* bacteria. The findings of the study clarified the process of CH_4 reduction in the rumen and the genetic selection method applied in their study decreased the rumen volume and increased the passage rate. From their study, it was suggested that the manipulation of the rumen microbiome seems to be a better method, but it requires further studies to investigate its different aspects.

Choudhury et al. [75] discuss the problems and benefits associated with alternate pathways for Enteric CH_4 reduction, such as reductive acetogenesis, propionogenesis, sulfate, and nitrate reduction, which enables bypass H_2 production and accumulation in the rumen. CH_4 is produced in the rumen of animals by methanogenic archaea, which combine CO_2 and H_2 to form CH_4. The removal of this H_2 is essential, as its accumulation inhibits many biological functions that are essential for maintaining a healthy rumen ecosystem. Among the other pathways occurring in the rumen, including reductive acetogenesis, propionogenesis, nitrate, and sulfate reduction, methanogenesis seems to be the dominant pathway for H_2 removal. The authors propose that creating alternate hydrogen sinks, such as acetogenesis (acetogenic bacteria consume H_2 and CO_2 to form acetate in the rumen), would divert hydrogen away from methanogenesis, thereby reducing CH_4 production. However, the study also noted that many of the strategies that initially appeared to be promising turned out to be less sustainable on the industrial scale over an extended period. They concluded that the development of a long-term solution has likely been hindered by our still incomplete understanding of microbial processes that are responsible for maintaining and dictating rumen function.

4.3.2. Low-Cost Method for CH_4 Leakage Detection

Farhan M. et al. [76] attempted the development of a low-cost method for CH_4 leakage detection. In the same work, a promising new method was developed for detecting CH_4 leakage points, especially in cases where other methods are too expensive or impractical, which was tried for monitoring CH_4 leakage from the subsurface of natural gas fields. In the study, the low-cost method to detect CH_4 leakage points from the subsurface to the atmosphere used activated carbon. Commercially activated carbon (AC) was found to be the best adsorbent for CH_4, among zeolite and porapak, because it gave the highest adsorption capacity and most consistent performance in different experimental setups. The activated carbon could adsorb up to 1.187×10^{-3} mg-CH_4/g-AC. The specific amount of adsorbed CH_4 when the initial concentrations of CH_4 in tedlar bags were 200 ppm, 100 ppm, and 50 ppm was found to be 0.818×10^{-3} mg-CH_4/g-AC, 0.397×10^{-3} mg-CH_4/g-AC, and 0.161×10^{-3} mg-CH_4/g-AC, respectively. This indicates the competent sensitivity of the method to detect small leaks. Hence, in applications, the AC can detect concentrations of as low as 5 ppm CH_4 source, which is critical for environmental safety. In urban areas, low-cost sensors have been proposed for use in water distribution pipes to detect leaks [77]. A similar approach could be applied to gas distribution systems, using the low-cost CH_4 detection method to identify and monitor leaks. However, this method is not able to determine the total amount of CH_4 emissions in the field; it can only localize the location of CH_4 leakage. The handheld, portable laser CH_4 detector (LMD) was developed for use in industrial environments to detect gas leaks from a safe distance [78]. Since 2009, this technology has been used to quantify CH_4 emissions from cattle, sheep, and goats by measuring the CH_4 concentration in their breath. This shows that the approach can be adapted for different purposes, e.g., monitoring CH_4 emissions in livestock farming. Adding deep learning techniques to a cheap system for checking for micro leaks also suggests that cutting-edge technologies like machine learning could be combined with cheap detection methods to make leak detection more effective [79]. The method has the potential to be a useful tool for reducing CH_4 emissions from the oil and gas industry and other sources, although it still needs to be refined.

4.3.3. Efficient Direct CH_4 Oxidation Process—Monomeric Species Identification

Xu C. et al. [80] introduced a method for the identification of monomeric Fe species needed for an efficient direct CH_4 oxidation process. The study developed a method for controlling Fe loading in MOR-type zeolites called modified liquid ion exchange (mIE). The 0.260Fe/MORmIE catalyst showed an excellent catalytic performance in the direct CH_4 oxidation reaction, with a record high turnover frequency. Spectroscopic studies revealed mononuclear Fe ions as active sites, minimizing Fe heterogeneity and limiting oxide species formation. The mIE method is promising for Fe/MOR catalyst preparation. The mIE approach shows promise as a novel strategy to generate highly active and selective Fe/MOR catalysts for the direct CH_4 oxidation process. The results also deepen the knowledge of the intrinsic active location for the direct CH_4 oxidation process.

Furthermore, the scalability of the modified liquid ion exchange (mIE) method for catalyst preparation is very important for large-scale industrial applications. The key factors that affect the scalability of the modified liquid ion exchange (mIE) method for catalyst preparation include:

i. Reproducibility and Consistency: Ensuring the reproducibility and consistency of the mIE method at a larger scale is essential. Maintaining uniformity in the modification process and the resulting catalyst properties across different batches is crucial for scalability.
ii. Process Engineering and Equipment: Scaling up the mIE method may require process engineering to ensure efficient mass transfer and reaction kinetics. Additionally, the availability of suitable equipment for large-scale implementation is a key factor in the scalability of the mIE method.
iii. Economic Viability: The cost of the mIE method at a larger scale, including the cost of raw materials, equipment, and energy, is a significant factor in its scalability. Assessing the economic viability of the method for large-scale catalyst preparation is essential.
iv. Environmental Impact: Scaling up the mIE method should consider its environmental impact, including the generation of waste, energy consumption, and the use of potentially hazardous materials. Evaluating and mitigating the environmental implications of the method is important for its scalability.
v. Quality Control and Characterization: Maintaining the quality and performance of the catalysts at a larger scale through rigorous quality control and characterization methods is a critical factor in the scalability of the mIE method. Ensuring that the modified catalysts meet the required specifications is essential.

These factors collectively influence the potential for the large-scale adoption of the mIE method for catalyst preparation and addressing them is crucial for its successful scalability. Despite these challenges, the mIE method has the potential to be a valuable tool for the preparation of supported metal catalysts. With further research and development, the scalability, cost, and environmental impact of the mIE method can be improved, making it a more attractive option for large-scale catalyst production. The specific challenges and potential of the mIE method will vary depending on the specific catalyst being prepared and the desired application. There are several ongoing research efforts aimed at improving the mIE method, including the development of new ionic liquids, continuous processes, and more cost-effective methods for catalyst recovery.

4.3.4. Use of Industrial By-Products as Supplements for Low-Quality Diets

Gere et al. [81] investigated the effects of dietary dry distilled grains with soluble (DDGS) inclusion on dry matter digestibility (DMD) and enteric CH_4 emissions. The experiment demonstrated that supplementation with DDGS in low-quality roughage reduced daily CH_4 emissions, yields, and Ym. Diets containing DDGS increased DMI by 22% ($p < 0.05$) and reduced daily CH_4 emissions by 24% (g/d), the CH_4 yield by 35% (g/kg DMI), and the average value of CH_4 energy per gross energy intake (Ym) by 44%, compared to the control treatment ($p < 0.05$). This is significant as CH_4 is a potent GHG and reducing its emissions is crucial for mitigating climate change. The results of this study suggest that supplementing low-quality feed with industrial by-products could be an effective strategy to reduce CH_4 emissions while providing a cost-effective source of nutrients for the animals.

Mohite et al. [82] investigated the possibility of using methanotrophs as bio-inoculants to promote the growth of rice plants, which may lead to a reduction in CH_4 emissions. Rice fields are a major source of CH_4 emissions caused by humans. The methanotrophs that live in the oxic–anoxic interface of rice fields and near the roots of rice plants can break down a lot of the CH_4 that is produced, so they are very important for managing CH_4. The study evaluated the bioinoculant potential of ten indigenously isolated methanotrophs from eight different genera, including four recently described genera and species (*Methylocucum oryzae*, *Methylolobus aquaticus*, Ca. *methylobacter oryzae*, and Ca. *methylobacter coli*) and two consortia (*Methylomonas* strains and *Methylocystis methylosinus* strains). Nitrogen fixation pathways, or nifH genes, were found in all twelve methanotrophs, but only nine of them helped rice plants grow (6–38%) compared to the control rice plants that were not inoculated. These nine plants were made up of two consortia and seven individual strains. *Methylobacter coli* (38%), the *Methylomonas* consortium (35%), and *Methylocucumis oryzae* (31%) produced the three highest grain yields. The research results illustrate the potential of using methanotrophs as bioinoculants for rice cultivation in the near future, facilitating growth with minimal use of nitrogen fertilizers. Further research has been proposed to comprehensively determine the effectiveness of using methanotrophs as bioinoculants in rice cultivation.

4.3.5. CH_4 Storage via Hydrate Formation

Ganteda et al. [83] compared the use of soybean powder (SBP) as a promoting additive with sodium dodecyl sulfate (SDS) for CH_4 hydrate production. The study found that the temperature and pressure of CH_4 hydrate production with SBP were 277.8 $\pm$ 3.2 K and 7050.9 $\pm$ 76.2 kPa, respectively, identical to SDS 277.2 $\pm$ 0.3 K and 7446.3 $\pm$ 5.7 kPa in the unstirred system. Furthermore, the study emphasized the importance of SBP as a non-foaming, biodegradable, renewable, and affordable gas storage material. With SBP and SDS, a gas absorption capacity of approximately 94.2 $\pm$ 4.5 v/v and 92.4 $\pm$ 4.6 v/v, respectively, was achieved, which corresponds to ~60% of the realistic feasible limit. The results show that it is possible to discover suitable biological and renewable promoters such as SBP to generate CH_4 hydrates with 100% conversion, paving the way for real CH_4 or natural gas storage and transportation in hydrate form.

The use of soybean powder (SBP) or other biological promoters for CH_4 hydrate production can contribute to the safe and efficient storage and transportation of natural gas. CH_4 hydrates are a promising alternative to traditional natural gas storage methods due to their high storage capacity and low environmental impact. However, the formation of CH_4 hydrates is a slow process, and the addition of biological promoters such as SBP can significantly accelerate the formation rate. SBP contains proteins and amino acids that can act as nucleation sites for CH_4 hydrate formation, leading to the faster and more efficient storage of natural gas. Additionally, SBP is a renewable and low-cost material, making it an attractive option for large-scale applications. The use of SBP or other biological promoters can also improve the safety of natural gas storage and transportation by reducing the risk of gas leakage or explosion. Overall, the use of biological promoters such as SBP can contribute to the safe and efficient storage and transportation of natural gas, making it a promising area of research for the energy industry.

Safety considerations related to CH_4 hydrate-based storage and transportation include the handling of hydrate formation and potential risks. CH_4 hydrates can be used for gas storage and transportation, but they also pose safety challenges. The formation of CH_4 hydrates should be carefully managed to prevent blockages in pipelines and equipment. Additionally, the potential risks of CH_4 release due to hydrate dissociation, which can lead to fire or explosion under certain conditions, must be addressed. Furthermore, the "self-preservation" effect of CH_4 hydrates, which allows for storing a substantial amount of gas locked in gas hydrate far outside its thermodynamic stability zone, should be considered in safety assessments [84,85]. Proper handling procedures and risk mitigation strategies are essential for the safe storage and transportation of CH_4 hydrates.

Bavoh et al. [86] did a review on the performance of biosurfactants for the enhancement of gas hydrate formation. They reviewed the effect of thermodynamics and the kinetics of hydrate formation. It was concluded that biosurfactants are an ideal molecule that could replace conventional surfactants in gas hydrate-based technologies. They recommended further study to fully understand the role of biosurfactants on gas hydrate promotional mechanisms and their potential for commercial future hydrate-based technologies.

The commercial viability of using biosurfactants for enhancing gas hydrate formation has been a subject of research in recent years. Biosurfactants, which are surface-active agents of biological origin, can potentially replace synthetic surfactants and provide several benefits, including cost savings and improved efficiency [85]. Some of the key findings from studies on biosurfactants and gas hydrate formation include:

i. Thermodynamic and kinetic impacts: Biosurfactants can enhance the formation of gas hydrates by increasing the nucleation time and hydrate formation rate [86]. For example, the use of glycolipids as biosurfactants has been explored for CH_4 hydrate generation, showing promising results in terms of thermodynamics and kinetics [85].
ii. Reduced induction time: Biosurfactants can significantly reduce the induction time of hydrate nucleation, leading to the faster formation of gas hydrates [84]. This can be beneficial for applications such as natural gas storage and transportation, as well as CO_2 capture and sequestration.
iii. Enhanced hydrate growth rate: Biosurfactants can also improve the growth rate of gas hydrates, leading to higher hydrate formation rates [84]. This can result in increased efficiency and reduced costs in various applications, such as gas separation and cold energy storage [87].
iv. Environmental benefits: Biosurfactants are often more environmentally friendly and stable at extreme conditions like temperature, pH, and salinity compared to synthetic surfactants [85]. This can make them a more sustainable option for gas hydrate formation, transportation, and storage applications.

However, it is essential to note that the commercial viability of biosurfactants for gas hydrate formation depends on various factors, such as the specific biosurfactant, concentration, and application conditions. Further research and development are needed to optimize the use of biosurfactants in gas hydrate applications and to fully understand their potential benefits and limitations [88,89].

4.4. Nexus of CH_4–X

This section delves into the complex connection between CH_4, with a specific emphasis on the underlying scientific aspects and prospective energy solutions such as gas hydrate mechanisms, growth rates and morphologies from CH_4-containing mixtures, oxidative coupling, catalysis, and synthesis. These solutions hold considerable promise in enhancing our comprehension and usage of this readily available hydrocarbon.

Chromatography techniques are fundamental for analyzing CH_4 in various applications like gas hydrates, power-to-gas, reforming, and oxidative coupling. Due to the advantages of accuracy, anti-interference capability, adaptability to different applications, and cost-effectiveness [90], gas chromatography (GC) is often used consistently, involving sampling, preparation, and chromatographic analysis for the accurate detection and quantification of CH_4 concentration.

4.4.1. Gas Hydrate Mechanisms, Growth Rates, and Morphologies from CH_4-Containing Mixtures

Martinez C. et al. [91] studied the growth rates, mechanisms, and morphologies of gas hydrates formed by CH_4, CO_2, and their mixtures. The study used advanced imaging and temperature control to study the growth rates, mechanisms, and morphologies of the gas hydrates of CO_2, CH_4, and two of their mixtures (CH_4:CO_2, at 80:20 and 30:70 nominal concentrations). The authors resolved previous contradictions in the literature on the morphology of these guests. They showed that all guests studied can exhibit the same crystal behavior at low driving forces and low growth velocities.

Nevertheless, different crystal behavior was observed for each visitor when the growth rates increased. Regardless of the guest, the temperature profile, driving force, location within the droplet, or growth duration, all gases examined in the hydrates of this study showed partial dissociation during growth. This study is one of the most recent to demonstrate partial dissociation for CH_4, CO_2, and their mixtures for the first time. The findings have implications for the understanding and development of technologies for the production, transportation, and storage of gas hydrates. Moreover, the specific applications or industries where the growth rates and morphologies of CH_4-containing gas hydrates have practical implications include the following:

i. Natural Gas Production and Storage: Hydrate-based gas recovery: CH_4 hydrates naturally exist in vast quantities beneath the seafloor and permafrost. Understanding how to control growth rates and morphologies could enable the efficient and targeted extraction of CH_4 from these hydrates, potentially providing a new source of natural gas. Hydrate-based gas storage: CH_4 hydrates can store large amounts of gas in a compact form. By tailoring the growth and morphology of hydrates, it might be possible to create efficient and environmentally friendly storage facilities for natural gas.
ii. Carbon Capture and Storage: Hydrate-based CO_2 capture: CH_4 hydrates can also incorporate CO_2. Controlling the growth and morphology of CO_2-containing hydrates could lead to new methods for capturing and storing carbon emissions from industrial sources.
iii. Gas Separation and Purification: Selective hydrate formation: As mentioned previously, the competition between different guest molecules like CH_4 and CO_2 can be used for gas separation. By controlling the growth conditions, it might be possible to selectively form hydrates with one type of guest molecule, leaving the other in the gas phase, leading to purer gas streams.
iv. Pipeline Plugging Prevention: Hydrate inhibitor design: Gas pipelines transporting natural gas through cold regions are susceptible to hydrate formation, which can cause blockages. Understanding the influence of growth rates and morphologies on hydrate formation could aid in the design of more effective hydrate inhibitors.
v. Fundamental Science and Engineering: Developing new materials: Studying the growth and morphology of gas hydrates can provide valuable insights into crystal growth and self-assembly processes, which can be applied to the development of new materials with tailored properties. These are just a few examples, and researchers are actively exploring the potential applications. As our understanding of gas hydrates grows and we gain better control over their growth and morphology, new and innovative applications are likely to emerge across various industries.

The challenges and opportunities related to gas hydrate dissociation during growth are discussed as follows.

i. Partial dissociation during growth: The study reveals that gas hydrates, including CH_4-containing ones, can undergo partial dissociation during growth. This phenomenon, where the hydrate releases some of its guest molecules while incorporating others, complicates the modeling of growth processes and hinders the prediction of hydrate behavior.

ii. Competition between guest molecules: When multiple guest molecules, like CH_4 and CO_2, are present, they compete for space within the hydrate structure. This competition can lead to unpredictable growth patterns and morphologies, making it difficult to control the formation of desired hydrates.

iii. Temperature and pressure dependence: Gas hydrate growth and dissociation are highly sensitive to temperature and pressure changes. This sensitivity poses challenges for practical applications where the precise control of these parameters is crucial.

iv. Tailoring hydrate morphologies: Understanding the mechanisms of dissociation during growth can open possibilities for tailoring the morphology of gas hydrates. This could be beneficial for applications where specific crystal shapes or sizes are desired.

v. Controlled dissociation for gas separation: The phenomenon of partial dissociation can be exploited for gas separation purposes. By manipulating the growth conditions, it might be possible to selectively release specific guest molecules from the hydrate, leading to purer gas streams.

vi. Enhanced gas storage and transportation: Gas hydrates can store large amounts of gas in a compact form, making them attractive for storage and transportation applications. If the challenges associated with dissociation during growth can be overcome, gas hydrates could become a more viable option for these purposes.

Overall, the growth rates and morphologies of CH_4-containing gas hydrates also present exciting opportunities for manipulating and exploiting this phenomenon for various applications. Further research is needed to fully understand the underlying mechanisms and translate them into practical advancements.

4.4.2. Oxidative Coupling of CH_4

The thermal cracking of CH_4 was examined by Mitoura dos Santos Junior et al. [92] as an alternative method to produce highly purified hydrogen that does not generate gaseous pollutants and produces solid carbon by-products that are commercially viable for other industrial applications around the world. The research used thermodynamic techniques, specifically entropy maximization and Gibbs energy minimization, to simulate the operating conditions of adiabatic and isothermal reactors. The chemical equilibrium and combined phases problem was written in a nonlinear programming language and solved with the CONOPT 3 solver. GAMS software was used to find the best solution. It is possible to crack CH_4 at high temperatures in adiabatic systems by adding hydrogen to the feed and setting up an extremely variable pressure system. The CH_4 conversion could range from 0% to 94.712% by setting the CH_4/H_2 ratio in the system feed to 1/10 at 1600 K and 50 bar and by performing strong depressurizations through an isentropic valve at different pressures from 50 to 1 bar. Their results were in excellent agreement with those found in the literature, with mean relative deviations of less than 1.08%. Elevated temperatures and reduced pressures promoted the decomposition of CH_4 and the formation of products. In an isothermal reactor, a complete CH_4 conversion took place at temperatures above 1200 K and a pressure of 1 bar. In an adiabatic reactor, on the other hand, CH_4 conversion rates were significantly higher at temperatures above 1600 K and 1 bar pressure. The amount of carbon produced did not significantly affect the process, as it is only produced after the reaction and heating processes. Under identical operating parameters, around 40.57% of the hydrogen produced can be used as energy for the process. This indicates a potential for industrial applications that require the production of hydrogen without the formation of CO_2. Although the thermal cracking of CH_4 does not produce polluting gasses, except for solid carbon along with hydrogen gas with a high degree of purity, this method still has a shortcoming in the handling of the produced carbon. It also provides an opportunity to investigate a wider range of operating conditions to refine the control and management technologies for industrial and pilot-scale CH_4 cracking.

4.4.3. CH_4 Synthesis and Catalysis

Godoi et al. [93] synthesized copper-doped palladium catalysts in different ratios supported by metal oxides such as $Sb_2O_5.SnO_2$ (ATO) catalysts for the conversion of CH_4 to CH_3OH. The catalysts produced contain Pd, CuO, and $Sb_2O_5.SnO_2$ phases with an average particle size of about 9 nm. When comparing the $Pd_{80}Cu_{20}$/ATO with other PdCu/ATO materials, the activity experiments revealed the maximum power density and the maximum reaction rate for CH_3OH production. The use of ATO as a support promoted the formation of CH_3OH from CH_4, while PdCu with a high copper content promoted the formation of more oxidized compounds such as carbonate and formate. Copper-doped palladium catalysts supported by metal oxides have practical applications in the conversion of CH_4 to CH_3OH. These catalysts have been found to be effective in the catalytic conversion of CH_4 to CH_3OH, leading to improved efficiency, reduced costs, and environmental benefits [76,77]. The addition of appropriate co-catalysts has been shown to enhance the photocatalytic activity of the catalyst, leading to more efficient and selective CH_4 to CH_3OH conversion [94,95]. The use of nanomaterials and metal–organic frameworks has been investigated to improve the catalytic performance of traditional catalysts [96,97]. The direct method of methanol production is desirable to reduce production costs and address environmental concerns. However, further research and development are needed to optimize the use of these catalysts and to understand their potential benefits and limitations fully.

Huang et al. [98] reviewed recent research on Ni-based bimetallic alloy catalysts for DRM. The study focused on the synergistic effects of the two elements, the role of the second metal and the reaction mechanism induced by different active sites. The importance of in situ experiments, density functional theory studies and combined quantum chemical calculations and experimental designs was emphasized to further elucidate the mechanism of action of alloy catalysts used for DRM reactions, the pathways of carbon formation during the reactions and the properties of the bimetallic alloys. The study recommends that future research should focus on the development of highly active and stable DRM catalysts with low cost. In addition, further studies should be conducted to understand the deactivation mechanisms of DRM catalysts and to develop methods for the regeneration of spent catalysts.

Marinho et al. [99] investigated the effects of metal dopants (Zr, Sm, and Gd) on the CeO_2 structure in the dry reforming of CH_4 using catalysts with embedded Ni nanoparticles. The results of the study show that doping the catalyst with Zr increases its thermal stability, which leads to the formation of tiny Ni nanoparticles. The addition of metal dopants, such as Zr, Sm, and Gd, to CeO_2 catalysts for the dry reforming of CH_4 yields several advantages. These metal dopants enhance thermal stability by preventing oxidation and inhibiting sintering, leading to a prolonged catalyst lifespan [99–101]. The catalysts also exhibit an improved catalytic performance, with enhanced redox properties, increased active sites, and optimized metal–CeO_2 interactions [101]. Furthermore, the metal dopants contribute to reduced carbon deposition, allowing for sustained catalytic activity and selectivity control [99]. This versatile catalyst design holds promise for more energy-efficient and economically viable processes in industrial applications.

Pacífico et al. [102] utilized fluidized bed reactors for CH_4-CO_2 reforming (MCR), i.e., converting CH_4 and CO_2 into syngas, a mixture of carbon monoxide and hydrogen. They used a Fluidized bed reactor with a nickel catalyst and ensured the optimization of their operating conditions, such as temperature, pressure, and the CH_4-CO_2 ratio. Fluidized bed reactors can achieve high conversion rates and low CH_4 slip (the amount of CH_4 that is not converted into syngas) under certain conditions. Specifically, a high temperature (800 °C), a low pressure (10 atm), and a nickel catalyst resulted in the best performance. Further research should be conducted to optimize the design of fluidized bed reactors for MCR. Also, research should be conducted to develop new catalysts. Fluidized bed reactors have significant implications in the dry reforming of the CH_4-CO_2 (MCR) process. The dry reforming of CH_4 with CO_2 is an endothermic reaction that produces synthesis gas with a lower H_2/CO ratio than that generated by the widely employed steam/CH_4 reforming reaction [103–105]. The use of fluidized bed reactors can improve the efficiency of the MCR process by providing better heat and mass transfer, leading to higher conversion rates and reduced carbon deposition.

Additionally, fluidized bed reactors can help address the challenges of catalyst deactivation and sintering, leading to longer catalyst lifetimes and reduced costs. Overall, the use of fluidized bed reactors has significant implications for improving the efficiency and sustainability of the MCR process. Optimizing the reactor design and operating conditions for an improved performance involves understanding reaction kinetics, selecting the right catalyst and support material, fine-tuning the temperature and pressure, optimizing the catalyst loading and particle size, controlling the reactant flow rates and residence time, preventing catalyst deactivation, managing heat effectively, considering the reaction equilibrium, addressing scale-up considerations, implementing robust monitoring and control systems, prioritizing safety, and minimizing the environmental impact. Continuous assessments and adaptations are essential for sustained optimal performance.

Alsudani et al. [106] reviewed the use of Fisher–Tropsch (FT) synthesis to convert CH_4 into liquid hydrocarbons through the gas-to-liquids (GTL) process. The development of more efficient and selective catalysts (nickel, ruthenium, and rhodium) has enabled the further development of FT synthesis, which includes the use of more efficient and scalable GTL reactors (fluidized bed reactors and slurry reactors). These new reactors are more suitable for commercial-scale GTL plants. The need to achieve the appropriate H_2:CO ratio when using a low steam-to-carbon ratio to develop newer catalysts, to develop the catalytic partial oxidation (CPO) process, and to reduce the capital cost of the plant was emphasized. Their study suggested that the ceramic membrane can be commercialized with improved mechanical, thermal, and chemical stability. Modifying the catalytic process to improve selectivity, developing new reactor systems, reducing production costs, producing high-octane gasoline, and improving selectivity to produce high-molecular-weight hydrocarbons were, therefore, required to develop a suitable catalyst layer and coating process for a specific configuration. FT synthesis and gas-to-liquids (GTL) processes have the potential to produce a range of valuable hydrocarbons beyond CH_4 conversion. FT synthesis is a key reaction in the utilization of non-petroleum carbon resources, such as natural gas and shale gas, to produce liquid transportation fuels. The process converts syngas (a mixture of CO and H_2) to a wide range of hydrocarbons, including straight-chain hydrocarbons in the paraffin series. GTL processes have been developed to convert natural gas into liquid hydrocarbons through FT synthesis, which offers a great option to use oilfield-associated gas and offshore gas fields. The use of metal catalysts, such as cobalt and iron, can improve the efficiency of the FT synthesis process. The potential for FT synthesis and GTL processes to produce valuable hydrocarbons beyond CH_4 conversion has significant implications for producing alternative energy sources and for reducing dependence on crude oil.

The main challenges associated with FT synthesis and gas-to-liquids (GTL) processes include high-energy consumption and costs, catalyst deactivation due to carbon deposition, and environmental concerns related to GHG emissions [107–109]. The production of liquid fuels from syngas using FT synthesis generates significant amounts of CO_2, which contributes to GHG emissions [110,111]. However, these processes offer opportunities for producing valuable hydrocarbons beyond CH_4 conversion, reducing dependence on crude oil, and producing cleaner alternative fuels. Further research and development are needed to optimize these processes and address the associated challenges. The main opportunities associated with FT synthesis and gas-to-liquids (GTL) processes include the utilization of non-petroleum resources, versatility in producing a wide range of hydrocarbons, and the production of cleaner alternative fuels [112]. FT synthesis enables the conversion of abundant natural gas and shale gas resources into liquid hydrocarbons, reducing dependence on crude oil [112]. The FT process produces a wide range of hydrocarbons, including straight-chain hydrocarbons in the paraffin series, which can be used as transportation fuels or as feedstocks for the chemical industry [113]. The FT process can produce cleaner diesel and other oxygenated compounds, such as alcohols and aldehydes, to meet the growing demand for cleaner alternative fuels [108].

Premachandra and Heagy [114] investigated the effects of morphology control on the photocatalytic partial oxidation of CH_4 to CH_3OH using WO_3, demonstrating that morphology control can be used to enhance the photocatalytic activity of WO_3 for the partial oxidation of CH_4 to CH_3OH. They carried out the synthesis and characterization (FESEM, PXRD, DRS, and XPS) of five different WO_3 morphologies: micron, nanopowder, rods, wires, and flowers, followed by an evaluation of the photocatalytic activity of each morphology by measuring the rate of methanol formation under UV light irradiation in the presence of 2 mM H_2O_2. WO_3 flowers exhibited the highest methanol productivity (38.17 ± 3.24 μmol/g-h), attributed to the 3D hierarchical structure of WO_3 flowers, which slows down the recombination of photogenerated electrons and holes and enhances the efficiency of the photocatalytic reaction. WO_3 flowers have relatively low bandgap energy (2.6 eV) and a high surface area (17 m2/g), which allows for the efficient absorption of visible light and the generation of hydroxyl radicals. The multiple reflections of light caused by the nanosheet-like (petal) structures of WO_3 flowers also increased the formation of photogenerated electron/hole pairs. Further investigation into the mechanism of methanol formation on WO_3 flowers and the optimization of reaction conditions to achieve even higher CH_3OH yields follows. Additionally, it explores the use of WO_3 flowers in other photocatalytic applications, such as the degradation of organic pollutants and the production of other valuable chemicals.

Premachandra and Heagy [114] also studied how morphology control enhances the photocatalytic activity of WO_3 and the partial oxidation of CH_4 to CH_3OH was studied. The photocatalytic activity of WO_3 for CH_3OH production has been found to be enhanced by a factor of approximately four by the addition of 2 mM H_2. The present study gives insight into the effects of morphology control over the surface area of WO_3 in the photocatalytic partial oxidation of CH_4 to CH_3OH. The photocatalytic activity of different morphologies was assessed via CH_3OH formation rates, and WO_3 flowers produced the highest CH_3OH yield. The morphology-controlled WO_3 has been found to be effective in the photocatalytic oxidation of CH_4 to CH_3OH in mild conditions. The study revealed that the photocatalytic activity of WO_3 toward methanol production has been enhanced by morphology control. The applications of WO_3 flowers extend beyond CH_4 conversion to include environmental remediation and wastewater treatment. WO_3 nanosheets and nanorods have shown promise in various applications, including photocatalysis for environmental remediation [115]. The increased surface area afforded by WO_3 nanosheets can benefit photocatalytic applications, making them suitable for water treatment and disinfection [116–118]. Additionally, the WO_3 band gap can be tuned for specific applications, such as the degradation of organic pollutants and water treatment [117–120]. Therefore, WO_3 nanosheets and nanorods hold the potential for addressing environmental challenges through their photocatalytic properties.

Pignataro Machado et al. [121] investigated the use of Pd/ZnO photocatalysts under mild conditions for the photocatalytic CH_4 conversion, demonstrating that Pd/ZnO photocatalysts synthesized by the borohydride reduction method are highly efficient. Alcohol-reduction and the Rorohydride-reduction methods were chosen for the synthesis of Pd nanoparticles supported on ZnO. Characterization was carried out using XRD, DRS, TEM, and XPS. Then, their efficiency towards the photocatalytic conversion of CH_4 under mild conditions was evaluated. The 0.5 wt% Pd/ZnO photocatalyst synthesized by the borohydride reduction method exhibited the highest C_2H_6 production rate (686 $\mu mol \cdot h^{-1} \cdot g^{-1}$) and selectivity (46%) attributed to:

- A smaller Pd nanoparticle size and better dispersion on the ZnO surface.
- The higher surface area of the Pd/ZnO from the borohydride method.
- Synergistic effect between Pd and ZnO.

Further investigation is needed into the mechanism of ethane production on Pd/ZnO photocatalysts and the optimization of reaction conditions to achieve even higher C_2H_6 yields. Also, the use of Pd/ZnO photocatalysts should be explored to produce other valuable chemicals from CH_4, such as CH_3OH and C_2H_4. The practical applications and implications of Pd/ZnO photocatalysts synthesized by the borohydride reduction method for the conversion of CH_4 to C_2H_6 involve the enhancement of selectivity towards C_2H_6 production. The addition of Pd to ZnO changes the selectivity of the production of C_2H_6 and CO_2, with 1.5%-Pd/ZnO being considered the best photocatalyst for the desired C_2H_6 product [122]. The photo-induced electrons and holes are effectively separated and utilized, leading to considerable quantum efficiencies. The highest selectivity for C_2H_6 reaches 72.6%, indicating the potential of Pd/ZnO photocatalysts for the selective production of C_2H_6 from CH_4 [106]. The work provides a new strategy for improving the photocatalytic reaction, and the Pd/ZnO catalyst shows excellent properties in this novel synergistic photocatalytic pathway. The high quantum yield observed at specific wavelengths and the role of the CH_3 radical in the formation of C_2H6 further highlights the potential of Pd/ZnO photocatalysts for the conversion of CH_4 to C_2H_6 under mild conditions.

Maia et al. [123] investigated the use of different proportions of AU-doped Pd anodic electrocatalyst for the conversion of CH_4 to CH_3OH on an ATO (Antimony-doped Tin Oxide) support. The study used Transmission Electronical Microscopy, a Cyclic Voltameter, Diffractometer, Raman Micro Spectrometer, polarization curves, and FTIR analysis for the determination of the optimal composition of AU-Pd in the conversion process. They found out that at the optimal composition of AU-Pd, the conversion of CH_4 to CH_3OH was well pronounced. The successful scalability and practical implementation of Au-doped Pd electrocatalysts for large-scale CH_4 conversion processes require considerations of synthesis scalability, catalyst stability, process efficiency, integration into the existing infrastructure, economic viability, safety, environmental impact, regulatory compliance, and technological readiness. Careful optimization and adherence to these factors contribute to the successful deployment of electrocatalytic CH_4 conversion technologies on an industrial scale. The high cost and scarcity of noble metal catalysts, including Pt, Au, and Pd, are noted as obstacles to their large-scale applications in electrochemical CO_2 reduction and other energy and environment applications [122,124,125]. Further research and development are needed to address these challenges and optimize the practical implementation of electrocatalysts for large-scale CH_4 conversion processes.

4.5. Case Studies' Application in Countries

The potential inherent in using the several categories of CH_4 advancements provided in this study at the national level has been thoroughly investigated by researchers. Table 4 provides an outline of a few examples of the utilization and the implications.

Table 4. Selected case studies of CH_4 mitigation applications in top CH_4-emitting countries.

Countries	Description of Application	Method/Category	Summary and Implication	Refs.
India	A virtual plant was developed using a mathematical model for the biomethanization of crop residue in India to mitigate the burning of stubbles. Focusing on India's small-scale farmers, the research used the ADM1 mathematical model to develop a fictitious biogas facility.	Computational modeling	The mathematical simulation of agricultural waste showed that 9–10 m^3 of CH_4, or 90–100 kWh of power, might be produced daily. The process stability and pH avoidance were both attributed to the co-fermentation with animal manures. The study recommends that policymakers and farmers investigate the use of less harmful alternatives for burning stubble to lessen its negative effects on the environment and public health.	[126]
Europe (EU)	This study examines the methanation component of Power-to-Methane (PtM) in 2050, focusing on scenarios with 80–95% CO_2 reduction. Capacity deployed across the EU is 40 GW, increasing to 122 GW when liquefied CH_4 gas is used for marine transport. Annual costs range from 2.5 to 10 blnEUR/year	Systems modeling	The results show that PtM arises for scenarios with 95% CO_2 reduction, no underground storage, and low CAPEX. Systems' drivers favor PtM more in determining PtM potential than technological drivers because of the poor CO_2 storage potential. Hence, direct subsidy is more effective than taxing fossil gas.	[127]

Table 4. *Cont.*

Countries	Description of Application	Method/Category	Summary and Implication	Refs.
Brazil	Data on the amount of waste disposed of in the landfill from 2002 to 2018 and the gravimetric composition of the waste estimated based on data from Porto Alegre, the municipality with the largest contribution of waste to the landfill, were analyzed and estimated.	Measurement and Integrated modeling (first-order decay models of LandGem, CDM Tool, and IPCC resources)	This study found that peak CH_4 gas generation in landfills will occur in 2026, with estimates ranging from 107,000 to 28,000 cubic meters per year. First-order decay models can estimate CH_4 gas generation potential, but accuracy can be affected by landfill characteristics and waste disposal. The implications of the study include informing landfill design, operation, and CH_4 gas capture and utilization. By understanding CH_4 gas generation potential, landfills can be designed and operated to minimize emissions and maximize energy recovery potential.	[128]
Russia	The Russian government's policy framework for reducing CH_4 emissions and the role of the oil and gas industry in implementing this policy were outlined. An overview was also given of the status of CH_4 emissions from the oil and gas sector in Russia and the challenges and opportunities for reducing these emissions.	Qualitative modeling	This framework emphasizes a comprehensive approach with various interconnected actions and incentives to effectively manage CH_4 emissions within the Russian oil and gas sector. By focusing on improved data collection, technological solutions, stricter regulations, financial incentives, international cooperation, and continuous improvement, the policy aims to mitigate CH_4 emissions and contribute to global climate efforts.	[129]
USA	The previously unquantified contribution of CH_4 emissions from groundwater pumping to the overall US CH_4 budget was investigated.	Measurement and Estimation Method: Aquifer selection, data acquisition, emission estimation	The study discovered substantial CH_4 emissions from groundwater pumping, with peak estimates for the Los Angeles Basin (LAB) aquifer reaching 2.9×10^{-3} Tg/a (Teragrams per annum) in 2026. For Northeastern Pennsylvania (NE PA), lower emissions were observed due to the lower CH_4 concentrations and pumping volume. Therefore, by encouraging further research and collaboration, this study paves the way for the improved understanding and potential mitigation of this unaccounted-for source of GHG.	[130]
China	The status of coalbed CH_4 (CBM) exploitation in China was reviewed, and suggestions for improving its efficiency were provided.	Literature review method	The study's findings have several implications for the future of CBM exploitation in China. First, there is a need for continued investment in research and development to develop new technologies that can improve the efficiency of CBM exploitation. Second, the government needs to implement policies that support CBM development, such as providing tax breaks and subsidies for CBM producers. Finally, the industry needs to work together to develop best practices for CBM exploitation. If these recommendations are implemented, China can unlock the potential of its vast CBM resources and play a leading role in the global energy market.	[131]
Ethiopia	The potential of fodder plants to reduce CH_4 emissions while simultaneously improving animal productivity in Ethiopia. Furthermore, the CH_4 production of seven forages, including three tropical multipurpose trees (*Leucaena leucocephala*, *Moringa stenopetala*, and *Sesbania sesban*), one shrub (*Cajanus cajan*), two legumes (*Crotalaria juncea* and *Lablab purpureus*), and maize stover, which is a widely used feed for ruminants.	Mixed-method approach: quantitative and qualitative data collection methods	This study implies that farmers can reduce CH_4 emissions from their livestock by feeding them a diet that includes M. stenopetala, C. juncea, or L. leucocephala. These forages are not only high in CP, but they also have the potential to reduce CH_4 production by up to 16%. This could have a significant impact on the environment, as livestock are a major source of CH_4 emissions. Additionally, these forages are also preferred by farmers, which suggests that they are a sustainable and practical solution for reducing CH_4 emissions from livestock.	[132]

5. Recommendation and Conclusions

CH_4 is a GHG, which is a significant contributor to global warming after CO_2. Therefore, several investigations have focused on significantly mitigating the emissions from CH_4 to make it a more sustainable resource. In this study, we projected the trends of emissions from CH_4 under baseline, low-, medium-, and high-subsidy reduction scenarios. The results were used to compute the GWP of CH_4 in comparison with actual projected CO_2 future values. The findings indicate that the scenario with a high subsidy cut has the potential to reduce the environmental impact of CH_4 emissions by bringing the GWP of CH_4 at least close to CO_2 levels. Hence, technological breakthroughs for the reduced environmental impact of continuous CH_4 utilization are pertinent.

In addition to the envisaged increase in CH_4 availability, the recovery from fossil resources, and separation and purification, CH_4 has great potential as a low-carbon fuel, offering several benefits over hydrogen, such as reduced expense, increased energy density, and simpler transportation and storage. V. Arutyunov et al. [133] presented the promising value of CH_4 in comparison to the more appealing option of hydrogen fuels. A variety of compounds, such as methanol and artificial Fischer–Tropsch (FT) products, which may be utilized as fuels or feedstocks for other industrial processes, can also be produced from CH_4. In the far future, thermonuclear fusion energy derived from CH_4 can be utilized to create syngas and other molecules [134]. This would enable the use of CH_4 by humans as a practical and sustainable energy source long after hydrocarbon supplies of industrial significance had been depleted. CH_4 is a flexible and sustainable energy source that has the potential to be extremely important in the world's shift to a low-carbon economy.

Our study, under five themes, has extensively reported the different advances that have been made in support of CH_4 management. These five themes include the measurement of CH_4, the applied modeling and simulation of CH_4, emerging technologies for CH_4 production, management, and control, CH_4 nexus, and the application of case studies in different countries.

Hence, our recommendations for increasing the mitigation of CH_4 emissions in line with the global climate goals, boosting industrial efficiency, and promoting sustainable practices across diverse sectors are as follows.

i. Adoption and Use of Best Practices: Transitioning to sustainable agriculture offers numerous benefits, including increased food security, reduced reliance on synthetic fertilizers, and reduced CH_4 leakage from natural gas systems. Implementing best practices in pipeline maintenance, leak detection, and storage technologies can boost the bottom line and mitigate the climate impact of natural gas. Additionally, reducing nitrogen-rich fertilizer runoff and proper manure management can improve aquatic ecosystem health and promote cleaner waterways.

ii. Closing Knowledge Gaps: Global CH_4 Mapping: develop comprehensive, high-resolution maps of global CH_4 emissions from all sources, including lakes, rivers, and anthropogenic activities. Marine CH_4 Processes: improve models to capture the complex dynamics of CH_4 release in ocean environments, considering factors like temperature, pressure, and biological activity. Anthropogenic Emissions: refine Earth system models to accurately predict the future trajectory of human-caused CH_4 emissions and their interactions with other GHGs.

iii. Optimizing Mitigation Strategies: Immediate vs. Delayed Mitigation: quantify the relative impact of immediate versus delayed CH_4 reduction efforts on achieving climate goals. Targeted Mitigation Strategies: identify and prioritize the most effective CH_4 mitigation strategies for each sector, considering cost-effectiveness and potential co-benefits. Technology Development: invest in research and development of novel technologies for capturing, storing, or utilizing CH_4 emissions, exploring both biological and engineering approaches. Pragmatic Financing: beyond the signing and an agreement for the employment of mitigation strategies, proper and timely finances should be made for the achievement of the strategies, hence matching words of mitigation with the real-time financing of development and the implementation of a technological breakthrough.

iv. Industrial Integration and Benefits: Real-time Monitoring and Optimization: develop AI-powered systems that combine modeling and sensor data to continuously monitor and optimize industrial processes for minimizing CH_4 emissions. Closed-loop Systems: design and implement closed-loop systems in relevant industries, such as biogas production or waste management, to minimize CH_4 escape and maximize resource recovery. Lifecycle Analysis: incorporate CH_4 modeling into lifecycle assessments of products and services to identify and reduce CH_4 emissions throughout the entire value chain.

The research presented in this study provides a comprehensive synthesis of various studies, offering valuable insights and perspectives on the current understanding of CH_4 utilization as a renewable and environmentally friendly energy resource, as per the selected database. This study highlights the significant progress made in various areas related to CH_4, including measurement techniques, production methods, conversion processes, cost-effective leakage detection, efficient oxidation methods, storage technologies, synthesis approaches, catalytic reactions, and its application in different countries. Each of the related study's recommendations based on acknowledged limitations have been identified, followed by proposed significant areas for future research. Overall, the summary of the presented research findings suggests that CH_4 has the potential to play a significant role in the global transition towards a low-carbon economic framework. Therefore, it is pertinent to have an increased allocation of resources to support the furtherance of research and development in CH_4 initiatives, with the aim of efficiently harnessing its potential.

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