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Review

Livestock Agriculture Greenhouse Gases for Electricity Production: Recent Developments and Future Perspectives

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Abstract: The focus of this review paper was to investigate innovations currently employed to capture and use greenhouse gases produced within livestock farms for energy production and expected future directions. The methods considered for data collection regarded a systematic review of the literature, where 50 journal articles were critically reviewed. The main findings identified that the conventional method used in transforming livestock agriculture greenhouse gases into energy regards the combustion of biogas. However, emerging methods encompass microbial fuel cells, dry biogas reforming, steam biogas reforming, auto thermal Chemical Looping Reforming (CLRa), and gas-to-liquid methods that convert methane to liquid hydrocarbons. The conclusions from the review are that there is a potential to integrate these methods in livestock agriculture in order to generate energy from greenhouse emissions and reduce the reliance on fossil fuels.

Keywords: livestock; agriculture; greenhouse; gases; electricity; production; trends

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Citation: Maraveas, C.; Simeonaki, E.; Loukatos, D.; Arvanitis, K.G.; Bartzanas, T.; Kotzabasaki, M.I. Livestock Agriculture Greenhouse Gases for Electricity Production: Recent Developments and Future Perspectives. *Energies* **2023**, *16*, 3867. https://doi.org/10.3390/en16093867

Academic Editor: Shahjadi Farjana

Received: 14 April 2023
Revised: 27 April 2023
Accepted: 27 April 2023
Published: 1 May 2023

1. Introduction

Over the years, the global livestock sector has grown in scale as the demand to feed the human population has also increased. Meat is an important source of nutrition in the world, and over the last 50 years, global production of meat has more than tripled, with current production at 340 million tons per year [1]. The direct implication derived from these livestock statistics is that larger farms have been established to support this mode of agriculture. However, several shortcomings are associated with the operation of large-scale livestock farms, despite their dominant role in supporting global food needs. One of these shortcomings regards the high generation of greenhouse gas (GHG) emissions from livestock agriculture [2].

In their study, Liu et al. [2] revealed that the livestock sector across the globe generated up to 710 million tons of CO_2-equivalent GHGs per year. Other research further indicated that livestock products and their by-products accounted for 18% of the total GHG emissions, 37% of the total methane (CH_4) emissions, and 65% of the total nitrous oxide (N_2O) emissions [3]. Research also indicates that the livestock industry adds directly to the anthropogenic GHG emissions from direct emissions through enteric fermentation and losses from manure, which account for 11% of the total emissions [4]. Additionally, the production of beef and dairy products generates the highest percentage of anthropogenic emissions, at 41% and 20%, respectively [5].

The Food and Agriculture Organization (FAO) statistics further consider enteric fermentation as a fundamental source of anthropogenic CH_4, where it contributed to 30–40% of the world's livestock emissions (CO_2-eq/year), closely followed by N_2O [6]. The World

Bank also indicates that the livestock sector annually generates an estimated 7.1 GT of CO_2-equivalent, which represents 14.5% of emissions that are human-induced [7]. Therefore, these statistics underscore the growing problem of increased greenhouse gas emissions associated with large-scale livestock farming and an urgent need to identify strategies to address the increased emissions.

The second challenge associated with livestock agriculture is the increased operating costs due to high energy consumption levels directly from on-farm operations, and indirectly when producing farm inputs, including concentrate feed [8]. Within livestock farms, energy is utilized in diverse ways, including producing, processing, and transporting feeds and powering the animal housing [9]. A further review [9] establishes that in the European Union (EU) livestock sector, animal feed is the largest energy consumer, where electricity is mainly used to cater to feeding and housing requirements and manure management. In addition, dairy livestock farming consumes high energy from milking, milk cooling, and heating water. Frorip et al. [10] additionally revealed that livestock farms consumed high energy levels both directly and indirectly in processing the animal feed, running machinery, and controlling the thermal environment during different seasons of the year.

Accordingly, the operation of large-scale livestock farms reveals an existent economic problem for stakeholders, who are constrained by high energy consumption and increased energy costs. Additionally, considering the increase in energy prices in different regions, such as the EU, farmers continue to experience high constraints in generating and maintaining profits within their farms [11]. The more recent Russia-Ukraine conflict in 2022 also contributed to the energy crisis as Russia, a global oil exporter accounting for 12.3% of the total supply in 2021, increased energy costs worldwide [12]. The use of fossil fuels to power livestock farms further exacerbates the greenhouse gas problem, since more emissions are generated by the consumption of electricity using such fuels on the farms.

The central argument advanced in this research paper is that although the livestock sector is integral in supporting the nutrition requirements of the growing global population, the continued use of fossil fuels as a source of energy for livestock farms is generating adverse consequences both economically and environmentally. Economically, the use of fossil fuels is straining farm operations due to high energy consumption levels and rising electricity costs. Ma et al. [13] demonstrated that an increase in energy prices led to a subsequent increase in production costs, thereby leading to welfare loss within a range of 0.6% to 1.4%. Furthermore, as livestock farms are energy intensive, both directly and indirectly [9], there is a need to identify alternative energy sources to ensure that demands are met at a cheaper cost. On a similar note, there is a need to identify alternative energy sources that can also minimize the GHG emissions linked to livestock agriculture and the use of fossil fuels as an energy source.

Therefore, the outcomes of this research are two-fold; first, they aim to detail innovations that contribute to reducing energy costs within the livestock farms. Second, they aim to reduce GHG emissions by transforming emissions from livestock operations into useful energy. Based on the scope of this article, the main focus is to examine innovations that capture and use greenhouse gases produced within livestock farms for energy production [14]. Two main GHGs that are produced from livestock farms include, as aforementioned, CH_4 and N_2O [15]. Grossi et al. [15] also reveal that CH_4 is mainly generated by enteric fermentation and the storage of manure, while N_2O arises from storing manure and using both organic and inorganic fertilizers. However, it is noteworthy that there are more sources of GHG in livestock agriculture, including land usage changes, such as cutting down trees, emissions from processing and transportation, and feed processing. Figure 1 illustrates the distribution of GHGs from livestock agriculture operations.

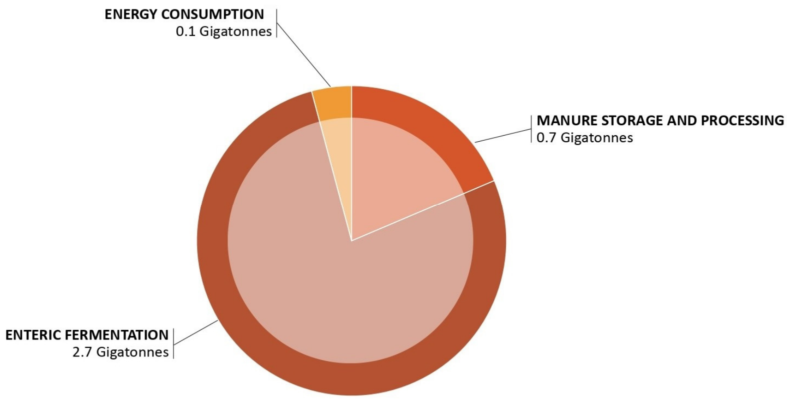

Figure 1. Greenhouse gas emissions (GHG) from livestock production [16].

According to Figure 1, enteric fermentation (CH_4) and manure storage and processing (N_2O) are identified as the main sources of GHG in livestock production. Therefore, the research focuses on innovations that capture and utilize CH_4 and N_2O for energy production.

The core focus of this article is to investigate the recent developments and future perspectives associated with generating electricity by capturing and utilizing the CH_4 and N_2O generated by livestock farms. The scope of the article encompasses a review of primary studies that examine technologies that capture greenhouse gases from livestock agriculture and transform them into energy. The following objectives will be addressed;

(i) To investigate the technologies employed to capture greenhouse gases from livestock agriculture.
(ii) To investigate the technological innovations employed to transform greenhouse gases from livestock agriculture into energy.
(iii) To identify future directions and emerging solutions that transform greenhouse gases from livestock agriculture.

The rest of the article is structured into four sections. Section 2 details the materials and methods. Section 3 details the results from the review of articles, while Section 4 discusses the results. Section 5 concludes the article, and key findings from the review article are detailed.

2. Materials and Methods

The systematic literature review (SLR) strategy was employed to collect the data in the current study. The systematic literature review methodology is distinguished from traditional reviews based on adherence to a pre-determined process when reviewing literature in a transparent and repeatable manner [17]. Therefore, an explicit methodology was adopted to answer the formulated research questions through the rigorous evaluation of the available literature. The justification of the SLR arose from the fact that it outlines a repeatable process through which the conclusions in the research can be generated.

2.1. Stage I: Identifying the Research Question

First, the core research question, which ought to be addressed in the review, was outlined as follows:

> *What innovations are currently being employed to capture and use greenhouse gases produced within livestock farms for energy production, and what future directions are expected?*

The SLR is centered around the research question that aims to address and subsequently motivate the research topic [17]. In the current paper, the focus was two-fold: to examine the current market and establish the innovations employed to capture and utilize greenhouse gases for energy production, and to investigate the potential future directions towards the advancement of the research area.

2.2. Stage II: Development of a Search Strategy

The second phase involved the development of the search strategy, where the parameters for the data search were specified, including the search keywords, databases, and inclusion and exclusion criteria guiding the study. The researcher identified scientific databases to obtain relevant articles, including Science Direct, MDPI, Springer Nature, and Sage. Thereafter, keywords were defined in order to facilitate the search for the relevant articles [18]. Aromataris and Riitano [18] argue that the definition of keywords and free-text words is the first formal step in the research, where they can be derived from article titles and abstracts as well as the literature. The keywords considered in this research included "innovations", "capture", "use", "greenhouse gases", "livestock farms", "energy", "production", and "future directions." The keywords were combined using the Boolean logic operators AND/OR in order to expand the scope of the search [19]. As a result, a wide range of resourceful articles were identified from the research.

2.3. Stage III: Study Selection

The initial search using the keywords and Boolean operators resulted in 620 articles across the different selected databases. Subsequently, the inclusion and exclusion criteria were applied in order to narrow the search's scope and reduce the number of articles included in the study. The inclusion criteria considered articles published within the last 15 years in order to ensure that comprehensive information was presented. The search also mainly adhered to the scope of the study regarding the innovations currently in use and those expected in the future to facilitate energy production from livestock greenhouse gases. Preference was also given to articles published in English to avoid extra work requirements and complications associated with translation [20]. Additionally, by only examining articles published in English, the researcher could fast-track the research process by eliminating the need for third-party translation services. The studies allowed in the research regarded journal articles completed using primary studies where data were collected from different technologies. The articles were also collected from different geographical regions to enhance the findings' comprehensiveness.

Full-text articles were also selected, while abstracts were not considered due to the limited available information. The exclusion criteria further eliminated articles that were beyond the scope of the research, where they either did not collect data using primary methods, or did not focus on greenhouse gases produced from livestock agriculture. For example, articles that focused on greenhouse gases from plant agriculture were not considered. The research also excluded review articles that were theoretical and did not provide empirical data on the research topic. Grey articles published on websites and personal blogs were also excluded due to their unreliability. Likewise, articles published in non-English languages, such as Chinese, French, and German, among others, were not considered in the research.

The quality of articles was assessed by utilizing the Critical Appraisal Skills Program (CASP) tool to examine the credibility and confidence rate of the quality of the summarized evidence in the research [21]. By using the tool, diverse questions were answered regarding the included studies, such as the clear aims of the research studies, the appropriateness of the research designs, whether the data was collected in an appropriate way, the rigor used in the data analysis, and the clear statement of the generated findings [22]. Appendix B details the application of the CASP quality appraisal tool in the assessment of the quality of the articles considered in this research.

2.4. Stage IV: Reporting the Findings

By employing the inclusion and exclusion criteria, 50 articles adhered to the established criteria and were incorporated in the final review, as detailed in the results section.

The articles were examined through thematic analysis, and key ideas were reported as themes. The PRISMA chart generated in Figure 2 below illustrates the search process adhered to in the review paper.

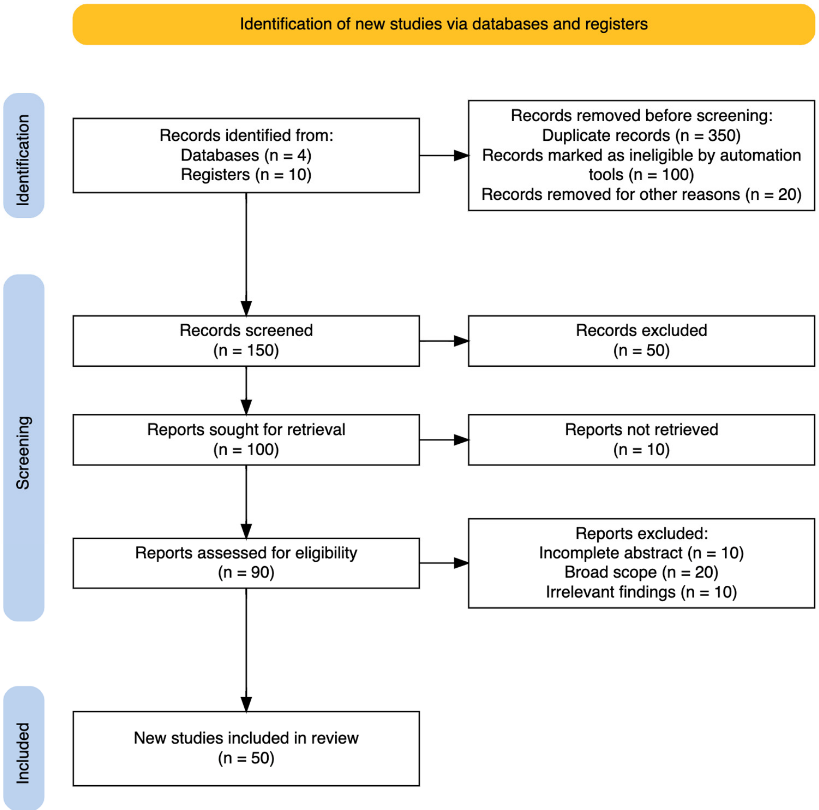

Figure 2. PRISMA chart.

3. Findings

3.1. Advances in Measuring GHG Emissions from Livestock Agriculture

A prerequisite to examining the technologies employed in transforming GHG emissions into energy was to review the mechanisms used in quantifying and measuring these emissions. However, there was a need to establish the sources of the different greenhouse gas emissions in order to link the technologies utilized in capturing and using the GHG emissions [23]. In their research, Graham et al. [23] revealed that CH_4 mainly arose from enteric fermentation, while N_2O was associated with the storage of organic manure. Therefore, the mechanisms employed for measurement track the release of the emissions from the respiration of the animals and in the housing where organic manure was stored. Tedeschi et al.'s [24] study was in agreement with these arguments and revealed that there are multiple methods that can be employed in the measurement of CH_4 and N_2O, including animal-based and facility-based techniques. The distinction between the two arises in that animal-based techniques focus on animals, while facility-based techniques are concentrated on housing facilities.

3.1.1. Animal-Based Techniques

Four animal-based techniques were examined in the systematic review, including direct gas exchange measurement, such as respiration chambers and spot sampling; tracer techniques; open-path laser methods; and in vitro and micrometeorological methods.

Direct Gas Exchange Measurement Techniques

Under the direct gas exchange measurement techniques, two key methods were widely adopted: respiration chambers and spot sampling.

Respiration Chambers

With the respiration chambers method, indirect calorimetry methodologies which rely on gas exchange—oxygen (O_2), carbon dioxide (CO_2), and methane (CH_4), are used to assess the composition of inflow and outflow air in open-circuit chambers or the composition of the air that has been accumulated over time in closed-circuit chambers [24]. A total of five studies were reviewed in order to examine how direct gas exchange measurement techniques were utilized in different livestock farms with open-circuit respiration chambers. Ganswothy et al. [25] argue that the indirect calorimetry respiration chamber is the gold-standard approach used in measuring enteric methane from ruminants, where the animal is confined in a chamber for 2 to 7 days. Thereafter, the methane concentration is assessed between the inlets and outlets and further multiplied by the airflow in order to indicate the rate of methane emissions [25]. Based on the wide popularity of the open-circuit indirect calorimetry method, the review investigated primary studies that employed the technique for methane measurement in enteric measurement.

Ku-Vera et al. [26] investigated the yield of methane from cattle that were fed on tropical grasses, including 66 Dry Matter Intake (DMI) and 42 Organic Matter Intake (OMI) considered. The research also examined heifers in open circuit respiration chambers which had a live weight of 288.5 ± 55.7 kg that were fed on the tropical grasses. An average intake of 8.22 kg DM and 7.8 kg OM was recorded for the heifers, with the open-circuit gas exchange measurement revealing an average CH_4 of 88 g per heifer daily [26]. The technique concluded that a methane yield of 18.07 g CH_4/kg DM intake was a consistent value that could be utilized for enteric CH4 inventories for cattle grazed in tropical grasslands in Mexico. Figure 3 illustrates the operation of the respiration chambers.

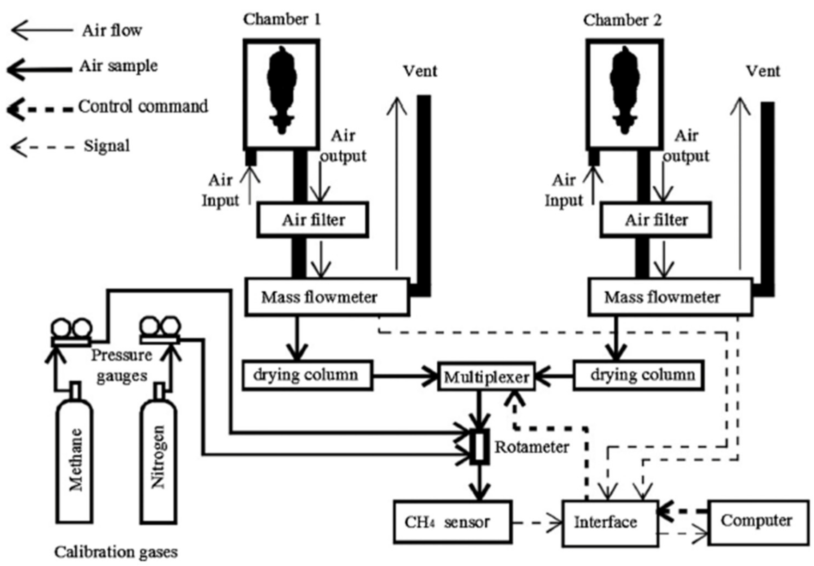

Figure 3. Respiration chambers [26].

In Figure 3, the operation of a respiration chamber is detailed, where breath from the animals in chambers 1 and 2 is directed to different vents for measurement.

Blümmel et al. [27] examined the intake of feed, digestibility, and methane production through open circuit respiration assessments in sheep fed with three types of wheat, oat, and barley straws; (i) untreated, (ii) sodium hydroxide (NaOH) treated, and (iii) anhydrous ammonia treated. The research also considered in vitro fermentation features of the straws that were generated from incubation utilizing the Hohenheim gas production system. The findings reported showed that the daily methane production from the open-circuit respiration chambers compared well with that from the in vitro fermentation features. Chagunda and Yan [28] also compared the level of agreement between methane measurement techniques—Laser Methane Detector (LMD) and open-circuit respiration calorimetric chambers—in the determination of the quantities of enteric methane from cows. The synthesis of [26–28] indicated a similarity across the different experiments, where open-circuit respiration chambers were identified as effective methods used in quantifying methane produced from enteric fermentation by ruminants. Comparisons were also made between the open-circuit respiration chambers and against laser methane detectors and in vitro fermentation, where the results showed that the methods generated similar conclusions.

Further research by Tomkins et al. [29] compared the open-circuit respiration chamber against a micrometeorological method to assess CH_4 emissions from beef cattle fed on Rhodes grass pastures in northern Australia. The study findings reported that using the micrometeorological method led to comparable methane quantities to those from the open-circuit chamber method—29.7 ± 3.70 g/kg dry matter (DM) vs. 30.1 ± 2.19 g/kg, respectively. Suybeng et al. [30] also considered beef cattle from Australia to measure methane from enteric fermentation. However, unlike [29], where a comparison was made between an open-circuit and a micrometeorological method, [30] compared the open-circuit respiration chamber against the greenfeed emission monitoring system and further supplemented the ruminant diet with Desmanthus. The conclusions reached in [30] showed no differences between the methane levels that were measured using the different techniques. Subsequently, the open-circuit respiration chamber method was widely adopted to obtain accurate and precise methane measurements.

Spot Sampling

The spot sampling method is the alternative direct gas exchange measurement technique where methane concentrations are measured in the breath of the ruminant for brief periods of time [24]. In this review, five articles were examined to investigate the application of different spot sampling methods in measuring methane. The techniques included automated head chamber systems, portable accumulation chambers, greenfeed monitoring systems, sniffers, and hand-held lasers. In the first study, Jonker et al. [31] used portable accumulation chambers (PAC) to assess carbon dioxide and methane emissions from ewes and lambs grazed on pasture that was based on ryegrass. The methane emissions were also compared against respiration chambers, where the results showed that the methane/methane + carbon dioxide ratio was comparable to the PAC and respiration chamber techniques [31]. Difford et al. [32] further compared methane measurements in sniffers and respiration chambers under commercial conditions for 20 lactating dairy cows. The generated results revealed a high correlation between methane produced from sniffers and respiration chambers—0.77 ± 0.18 vs. 0.75 ± 0.20, respectively [32]. The similarity in correlation scores indicated that sniffers both on the farm and in respiration chambers had a potential for the measurement of methane emissions from large-scale dairy cattle.

Sorg et al. [33] combined several spot sampling methods to assess levels of methane from cattle on a farm: these included hand-held laser methane detectors (LMD), the GreenFeed system (GF), and non-infrared breath analyzers (sniffers) that were implemented in the feeding bins of automatic milking systems. The assessment of the findings revealed that the use of different spot sampling devices facilitated the measurement of methane emissions on a daily basis, as a strong repeated measures correlation of LMD and GF was reported at 0.66. The results further confirmed that the different spot-sampling methods ranked the cows similarly. Castelán Ortega [34] also constructed a headbox respiration chamber suitable for small-scale applications where it was employed in measuring methane levels from eight cows—four Holstein cows with a live weight of 593.8 ± 51 kg, and four heifers with a live weight of 339 ± 28 kg [34]. The results from the use of the headboxes showed that the methane yields obtained from the cows and heifers—19.7 ± 3.4 g and 17.1 ± 3.4 g CH_4 kg^{-1} of dry matter, were comparable to those from the literature [34]. Figure 4 below illustrates the headbox respiration chamber constructed in [34].

Figure 4 details the schematic diagram of the open-circuit chamber utilized to measure methane from cattle.

Rey et al. [35] further compared the Non-Dispersive Infrared Methane Analyzer (NDIR), which is a sniffer method, against the hand-held Laser Methane Detector (LMD). The findings reported that there was a higher methane concentration with the NDIR sniffer (0.42) as compared to the LMD (0.23) [35]. The results further indicated that although there was a high concordance correlation coefficient between the CH_4 concentration for both methods, a difference emerged in the population means and variances between the instruments. Therefore, the research concluded that the LMD and NDIR were not interchangeable as they captured methane levels differently when used in livestock farms. However, further arguments suggested that the two methods could be combined in order to facilitate applications such as mitigation strategies and genetic selection purposes.

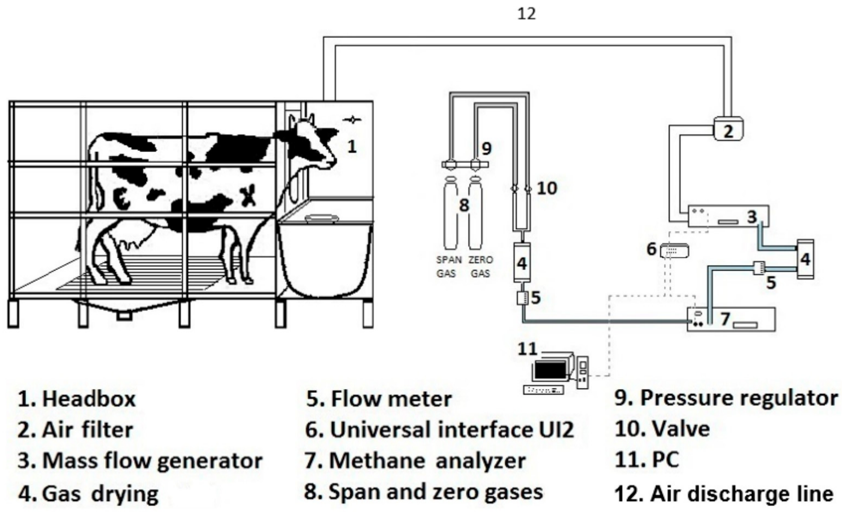

Figure 4. Ventilated hood-type open-circuit chamber [34].

A close inspection of the reviewed spot sampling methods [31–35] reveals several important insights. First, comparing these studies underscored their relevance in measuring methane levels from the ruminants during activities such as feeding and milking, where tubes were attached to feeding bins to detect methane near the animal nostrils. As such, the debate established that the spot sampling methods were useful in both small- and large-scale applications in measuring methane from ruminants.

Tracer Techniques

The tracer techniques emerged in scenarios with a focus on measuring the levels of methane emitted from the animals without confining them in chambers [25]. The method uses a tracer gas such as sulphur hexafluoride SF_6 that is generated from a bolus or permeation tube with a release rate that is predetermined within the rumen of the animal [24]. The air is thereafter sampled from the nostrils of the animal through tubes connected to a halter attached to its back or neck. A capillary tube is further used to restrict the flow of air through the tube so that it is nearly full after 24 h. To calculate the methane emission rate, the tracer gas known rate is multiplied by the ratio of expired methane gas and the tracer gas levels in the halter, while also considering the concentrations of the gases in ambient air [25].

In this review, three studies were examined to investigate the application of tracer techniques in methane measurement in different conditions. Moate et al. [36] conducted a study to investigate whether the SF_6 technique was affected by outdoor weather conditions, including relative humidity, rainfall, temperature, and wind speed. The study considered six cohorts of dairy cows, comprising 40 animals per cohort, that were fed on a similar diet for three years, and measurements for the methane were undertaken every five days over a 32-day period. The generated findings indicated that using the SF_6 technique was feasible in outdoor settings with varied conditions of humidity, rainfall, temperature, and wind speed. Doreau et al. [37] compared three methods used in measuring methane levels in enteric fermentation: open-circuit respiration chambers (OC), gas tracers (SF_6), and GreenFeed (GF), for eight cows that received diets comprised of 70% hay and 30% concentrates. The generated results showed that correlation coefficients for CH_4 emission and CH_4 yield were high and substantial for OC and $SF_{6,}$ while they were not significant between OC and GF and GF and SF_6 [37]. The implication of these results was that the differences in individual correlations made it difficult for the methods to be used interchangeably in small-scale applications where methane emissions were measured. Maciel et al. [38] also utilized the SF_6 technique to evaluate the influence of the composition of a breed on the performance and methane emissions for eight Nellore (NEL) and eight Angus x Nellore (AN) crossbred beef cattle. From the generated findings, it was observed that the NEL had less methane intensity in grazing and average daily gain as compared to the AN. The results also indicated that breed composition did not generate an impact on the methane yield based on dry matter intake (DMI). However, due to differences in average daily gain, the study concluded that crossbreeding was an effective strategy to reduce methane levels emitted per kg of meat produced.

The synthesis of the studies [36–38] established that the tracer techniques were viable in the assessment of methane from enteric fermentation in ruminants in outdoor settings. Additionally, insights established that the SF_6 technique generated comparable results to the OC, which was an indicator of the interchangeability between tracer techniques and respiration chambers.

Laser-Based Techniques

Laser-based techniques are also utilized in measuring methane from enteric fermentation in ruminants, and can be classified into two categories; the hand-held laser methane detector (LMD), a spot sampling method, and the open-path laser technique, which is more suitable in large-scale operations [39]. The difference between the LMD and open-path laser technique arises in the scope of the application, where LMD involves hand-held devices that are pointed at the nostrils of the animal to assess the methane column density along the laser beam's length [39]. However, the open-path laser techniques consider the quantification of dispersion for specific gas from the source and the downwind concentration of the gas to determine the total rates of emission using the inversion dispersion method [24]. The open path laser method is suitable for measuring CH_4 from herds of animals as they are feeding, while lasers and sensors are employed to send beams of light from the animals to open path tunable diode detectors, which analyze the CH_4 from the grazing animals through the IR-absorption spectroscopy technique [39]. Figure 5 illustrates the inverse dispersion method used in measuring methane from cattle in a paddock.

Figure 5 illustrates the IR-absorption spectroscopy method used to measure methane from grazing cattle.

To understand the applications of the inverse dispersion method, three articles were examined. Flesch et al. [40] employed the inverse dispersion method to assess the enteric methane concentrations from 15 cattle trials in three distinct conditions: summer grazing, winter feeding, and winter swath grazing. The methane emissions were also computed based on concentration differences between the measurement paths in narrow paddocks. The findings showed that there was good agreement between the IDM designs across the 15 trials and based on the consistent forage types. Additionally, the results revealed a methane yield of 23.4 g/kg of dry matter intake in winter grazing, 23.9 g/kg in winter feeding, and 21.3 g/kg in summer grazing [39]. The method indicated that open path laser techniques were feasible in scenarios where narrow paddock IDM were used, and generated advantages such as non-interference with the animals in their natural environments.

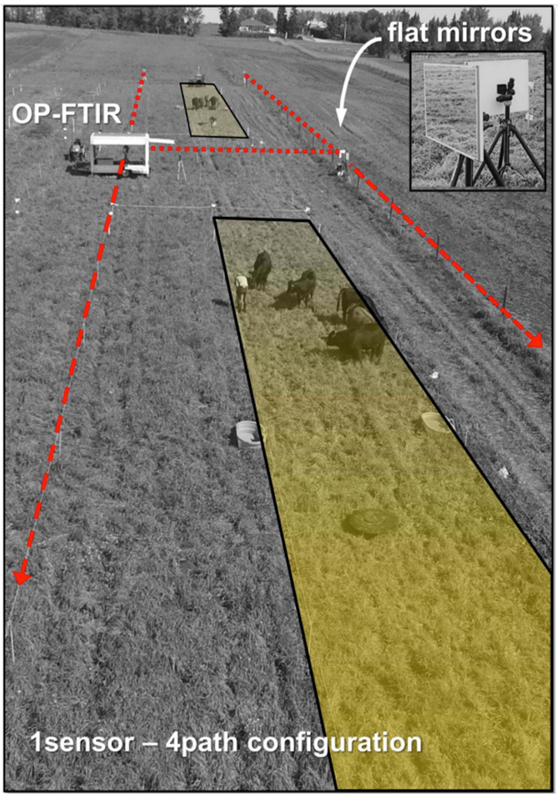

Figure 5. IR-absorption spectroscopy using one sensor and four paths [39].

Kang et al. [41] further demonstrated the use of LMD in methane measurement from enteric fermentation in cattle in intensive farming, where two separate experiments were conducted. The first experiment involved four Hanwoo steers, while the second collected data from 30 Hanwoo steers by installing the LMD on a tripod aimed at the animals' nostrils, and the CH_4 exhaled was assessed every 6 min per hour for two days [41]. The animals in experiment 2 were also fed different diets with high-energy concentrates in order to investigate methane emissions. The generated results showed that the LMD method was effective in measuring the methane emissions from cattle. Roessler and Schlecht [42] used the LMD method to measure the methane in four freely grazing goats that were in different conditions: restraint in a feed fence, and roaming while grazing. The LMD method was useful in determining whether the conditions that the goats were placed in had an influence on rumination activity and methane emissions [42]. The results generated showed that methane emissions did not vary under restraint (6.5 ppm-m) and free-roaming (6.6 ppm-m). However, higher CH_4 concentrations were established in the exhaled air from the ruminants during the afternoons as compared to morning sessions [42]. The insights from [41,42] indicated that LMD was important in the measurement of methane emissions from small-scale livestock farms, where ruminants such as goats and cattle were involved. The LMD could also be utilized in different scenarios where the animals were either freely-grazing or restrained, such as feed fences. The comparison of [41,42] against [40] also established that the LMD was suited to small-scale situations, while the open path laser technique was more appropriate where large herds of grazing animals were considered.

3.1.2. Facility-Based Techniques

The second category of methane measurement techniques regards the facility-based methods that consider the housing where the animal waste is maintained. The assessment of methods to measure CH_4 and N_2O emissions was subsequently undertaken.

Manure Storage

The premise of the manure storage methods is that methane is produced from its decomposition and can be measured by the examination of its levels in different storage facilities. The review examined studies that quantified methane emissions from slurry storage sites and biogas plants where manure was stored. Vergote et al. [43] used an on-line gas phase analyzer to quantify the CH_4 and N_2O emissions from farm-state mono-digested dairy manure through uninterrupted monitoring processes in an on-site digestate storage for a period of three months. The method is similar to the closed chamber approaches involved the accumulation of gases where the emission rate was quantified [43]. The results showed that methane emissions ranged from 4.6 to 14 g m^{-3} d^{-1} per day, while the nitrous oxide emission varied from 0.004 to 0.13 g m^{-3} d^{-1} [43]. The results further indicated that total emissions of the greenhouse gases ranged between 170 and 478 g [$CO_{2,\ eq}$.] m^{-3} d^{-1}, where only 10% was attributed to N_2O. Furthermore, increasing the volume of the digestate and the temperature also led to increased CH_4 and N_2O emissions. Figure 6 illustrates the closed chamber used in measuring methane and nitrous oxide.

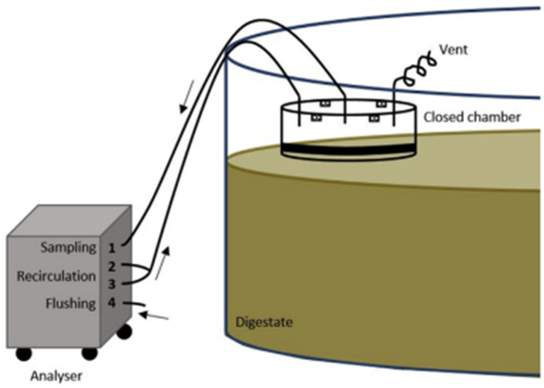

Figure 6. Closed chamber to measure methane and nitrous oxide [43].

Figure 6 illustrates the closed chamber that is useful in the measurement of methane and nitrous oxide from the digestate.

Vechi et al. [44] further utilized the tracer gas dispersion method to quantify methane emissions from five Danish pig farms that employed different methods for manure management. Three techniques were utilized for manure treatment; biogasification, acidification, and liquid slurry, where no treatment methods were used [44]. The generated results showed that farms with no manure treatment and where pigs were fattened had the highest methane emission rates, while the lowest methane emission rates were identified in farms with acidification manure treatment. The inference from [44] is that to capture more methane emissions from the manure storage which considers different types of animals, there is a need to avoid the manure's treatment through methods such as acidification. The analysis of [43,44] establishes that CH_4 and N_2O emissions can be captured directly from the livestock slurry through tracer gas dispersion and closed-chamber methods such as on-line gas phase analyzers. The findings indicate that to measure methane levels, manure storage systems ought to be constructed where the greenhouse gases can be trapped and measured.

Further review established the different factors that influence methane emissions from the closed-chamber systems. A noteworthy study is that of Cárdenas et al. [45], who investigated the impact of season, storage duration, and temperature on methane emissions from stored liquid dairy cow manure. The methane emissions from the winter periods were assessed in two intervals; 0 to 69 days, and 0 to 139 days, while in summer, four intervals were considered: 0 to 70 days, 0 to 138 days, 0 to 209 days, and 0 to 279 days, where probing was conducted every ten weeks [45]. The emissions of methane were determined at 20 °C for 60 days in eudiometer batches, where the results showed that the highest methane emissions were achieved in summer and after a period of 40 weeks at 0.148 kg CH_4 kg^{-1}, while in winter conditions, the highest emissions were attained after 20 weeks at 0.0011 kg CH_4 kg^{-1}. The implication of [45] was that storing the livestock manure in a liquid form (slurry) in conditions of higher temperature and over a long duration of time maximized the total methane emissions that could be generated. Hilgert et al. [46] also investigated how temperature and chemical composition changes affected methane emissions in livestock slurry sourced from livestock and pig slurry. The slurry was maintained at five different temperatures, from 5 °C to 25 °C, for a period of 90 days. The generated results showed that temperatures between 20 °C and 25 °C accounted for the highest methane emissions at a biochemical methane potential (BMP) of 69.3% and 50.3%, respectively [46]. Ma et al. [47] investigated the impact of manure storage methods that involved exporting pig slurry to outside storage locations on methane and ammonia emissions levels. The generated results showed that frequent export of slurry to external storage led to more ammonia emissions and lower methane emissions [47]. Such insights indicated that delaying the residence periods of the pig slurry within the in-house storage led to the reduction of the total methane emissions that were generated.

The discussion of [45–47] underscores the importance of temperature and a long duration of time for storing livestock manure in order to maximize the emissions generated. The insights also established that longer storage periods for the livestock slurry would also result in higher methane and ammonia emissions from the manure.

3.1.3. Emerging Techniques to Measure CH_4 from Ruminants

The review so far emphasized that the conventional methods employed in measuring methane emissions from ruminants encompassed animal-based and facility-based methods. The differences between them arose from animal-based methods assessing methane from the animals, while facility-based techniques measured methane from the closed chambers where manure was stored in a slurry form. However, further review established that there were emerging methods that consider other techniques to measure methane, as discussed in this section.

Blood CH_4 Concentration Tracer

With this method, methane obtained from a blood sample of the jugular vein of the ruminant is quantified through SF_6 tracer gas introduced through an intraruminal bolus in the rumen [40]. The premise of the method is that methane released through enteric fermentation travels up through the bloodstream once it is absorbed in the rumen walls. The blood in the pulmonary artery is sampled before it is transported to the lungs to be expired in the lungs [40]. As a result, the use of the concentration tracer technique provides a snapshot of the concentration of methane during the sampling period.

Infrared (IR) Thermography

The IR thermography technique involves using infrared thermographic cameras to measure the changes in temperature on different surfaces [48]. The method is a non-invasive and inexpensive technique adopted to detect methane emissions from ruminants by assessing changes in temperature in the rumen [40]. In this case, a thermal imaging camera is used to assess flank temperature on cattle, where differences in temperature between the right and left flanks indicate the methane emissions in the particular animal [38]. The underlying argument associated with the uptake of the IR thermography method is that since it is effectively used to measure changes in surface temperature during illness and infections, the technique can also be utilized in the analysis of rumen activity to determine whether methane is emitted.

Intraruminal Telemetry

The intraruminal telemetry method involves the use of IR sensors and wireless networks to measure the concentration of different gases, including methane, carbon dioxide, and hydrogen, in the rumen by utilizing intraruminal devices [49]. With this method, intra-rumen devices that are fitted with gas sensors and that communicate through wireless networks log the concentrations of methane and other gases within the rumen [49]. As a result, real-time data is relayed during the enteric fermentation processes.

Eddy Covariance (EC) Technique

With this method, technologies such as optimal sensors are employed to assess how gas and energy are exchanged, as well as the momentum between the different ecosystems [50]. However, to effectively use the method, knowledge of the total number of animals and their locations within the footprint is important. An explanation is that footprint calculations are used to estimate cattle emissions and further interpret the associations between flux derived by the eddy covariance and the emissions at the different footprint locations [39].

Prajapati and Santos [50] combined the EC and carbon dioxide tracer methods to estimate methane emissions from cattle in a feedlot in Kansas. The results from the technique established consistent methane emissions in the CO_2 tracer method and the EC techniques with only 3% deviations reported during dry and cold months [50]. However, during the warm and wet months, there was a minimal agreement between the CO_2 tracer method and the EC techniques. Dumortier et al. [51] also combined the EC techniques with geolocation and a footprint model with a view to measuring outdoor methane emissions from grazing Belgian Blue cattle. The results from the method revealed an estimate of methane emissions of 220 ± 35 g CH_4 LU^{-1} day^{-1}, which indicated methane emissions per livestock unit per day [51]. Stoy et al. [52] utilized the eddy covariance technique to assess methane and carbon dioxide flux from a bison herd on an enclosed pasture during both winter and summer. The generated results showed that in the absence of the bison, methane emissions were negligible in the study area, but were greater than zero when the bison were incorporated 0.048 ± 0.082 μmol m^{-2} s^{-1} for the mean and standard deviations [52].

Carbon Dioxide as a Tracer Gas

This method is similar to the utilization of SF_6 as a tracer gas in quantifying methane emissions, with the difference being that CO_2 is used to calculate the levels of CH_4 emissions from enteric fermentation methods [40]. With this method, it is argued that there is a relation between heat and CO_2 production, and as such, the ratio of CH_4: CO_2 in exhaled breath can facilitate the calculation of CH_4 emissions. Huhtanen [52] used CO_2 as a tracer gas to determine methane emissions for 307 cow-period observations from two different locations, and compared them against respiration chambers. The cows considered were ranked as low, medium, and high efficiency based on the intake of residual feed and the production of residual milk [52]. The results showed that efficient cows produced less heat and less CO_2 per body weight than inefficient cows, which challenged the use of the carbon dioxide method as a tracer gas. The results further revealed an overestimation of methane emissions by 17% for the low-efficiency cows, indicating that the method favored low-efficient cows. Examining the carbon dioxide tracer method for estimating methane gas emissions reveals that it is challenged by issues such as overestimation and bias where low- and high-efficient cows are considered [52].

3.2. Technologies to Transform GHG Emissions in Livestock Agriculture into Energy

The review thus far has comprehensively discussed the methods employed to capture and measure the emissions of methane and nitrous oxide from livestock agriculture. The methods were classified into animal-based: respiration chambers, spot sampling, tracer techniques, laser-based methods; and facility-based: closed chambers used for manure storage. To advance the discussion, this section considers the current technologies employed in transforming GHG emissions from the methane and nitrous oxide emissions captured in livestock agriculture.

There is an assumption that the livestock farms implement the gold standard methods for methane capture and measurement, respiration chambers, and manure storage in the closed chambers. A further assumption is that in most small-scale livestock farms, anaerobic digesters are more economical to implement with regard to the capturing of the methane from livestock waste and using it in different applications. Therefore, the focus is to examine the nature of technologies that have been utilized to convert emissions into energy in livestock agriculture from existing anaerobic digesters or respiration chambers.

Kabeyi and Olanrewaju [53] argue that, conventionally, biogas is converted into electricity by using prime movers for power generation, including diesel engines, Stirling engines, and Otto cycle engines. Therefore, the methane from the closed and respiration chambers is directed to the different prime movers, where its combustion facilitates electricity generation by powering different types of generators. The review considered different articles which examined how biogas was used in conventional electricity-production generators. Yatim et al. [54] designed a Gamma V2-6 Stirling engine burner and implemented it in a biogas-fueled power generation system. The combustion of the biogas at the burner generated sufficient heat to power the Stirling engine and produced electricity [54]. The system utilized 165 kg/day of solid biowaste, generating a power of 5 kW capacity.

Abanades et al. [55] compared different electricity-generation approaches from biogas, including internal combustion engines and micro-gas turbine systems. The generated results showed that biogas was important in electricity generation, where it was associated with an efficiency of 8–54% [55]. Zia et al. [56] further argued that livestock waste from more than 15 million animals produced up to 4 million tons every year in Pakistan. The waste could be utilized through diverse technologies such as bio-methane engines, gas turbines, and steam turbines to generate more than 300 TWh of energy to serve the Pakistan population [56]. Barzegaravval et al. [57] further conducted an exert economic evaluation of a gas turbine system that was pre-heated using biogas, and the fuel composition of methane also changed in the study. The generated results showed that where the methane content was changed from 0.95 to 0.6, the total cost rate of the plant increased by 1%, while the electricity cost also increased [57].

The analysis of [54–57] establishes that the conventional approach to convert methane from livestock agriculture into electricity is through the combustion of biogas, which has a high concentration of methane and nitrous oxide. The gas and heat are burned to power different technologies, including bio-methane engines, bio-methane gas turbines, bio-methane steam turbines, micro-gas turbine systems, diesel engines, Stirling engines, and Otto cycle engines.

3.3. Emerging Technologies and Future Directions to Transform GHG into Energy

3.3.1. Microbial Fuel Cells

One of the emerging technologies regards microbial fuel cells, which utilize microorganisms to generate electrical energy from chemical energy contained in an organic matter [58]. The fuel cells comprise an anode that generates electrons from the oxidation of the organic matter and the cathode, where the electrons move to be consumed through reduction reactions of the oxidizing agent [58]. The generated electricity is thereafter stored within capacitors. The study [58] reversed microbial fuel cells' methanogenesis to generate methane electricity. The study combined engineered archaeal strain, producing methyl-coenzyme M reductase from unculturable anaerobic methanotrophs with *Geobacter sulfurreducens* and methane-acclimated sludge [58]. The archaeal strain captured the methane and further secreted acetate, while the *Geobacter sulfurreducens* generated electrons from the acetate that was generated [58]. The results showed that the power density and current density from the microbial fuel cell were comparable to other cells that used non-gaseous substrates such as *Shewanella* and *Geobacter* spp. [58]. The findings also showed that the methane MFC could power a fan by using the electricity stored in the capacitors.

McAnulty [59] constructed a synthetic consortium that comprised an engineered archaeal strain to produce methyl-coenzyme M reductase from anaerobic methanotrophs that were unculturable in order to capture methane and secrete acetate; micro-organisms from methane-acclimated sludge to facilitate the transfer of electrons; and *Geobacter sulfurreducens,* which produced electrons from acetate [59]. The generated results from [59] were comparable to [58], where the microbial fuel cell successfully converted methane directly into an electric current. Further results showed that adding micro-organisms in the sludge led to significant current amounts. The similarity between [58,59] arose in that both researchers utilized microbial fuel cells to transform methane into electricity by converting the organic matter into energy.

Ren's study [60] was in line with [58,59], where methane was directly converted into current by using a careful consortium of microorganisms. However, Ren [60] argued that there were diverse challenges faced, which hindered the use of the methane fuel cells whereby high-temperatures were required (650 to 1100 °C). Other challenges identified regarded the complexity of the anaerobic oxidation of methane and the difficulty in culturing the microbes [60]. Figure 7 illustrates the schematic diagram of the MFC developed in the study [60].

Despite the issues, [59] appraised microbial fuel cells, as they facilitated the direct conversion of methane into electricity without any leaks being observed in the transportation of the gas.

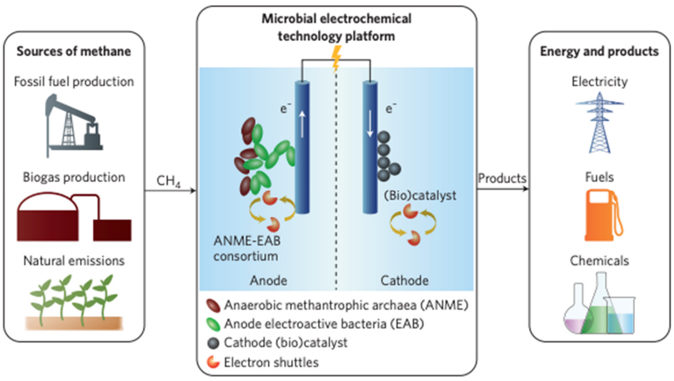

Figure 7. Schematic diagram of a microbial fuel cell [60].

Ding et al. [61] further demonstrated how denitrifying anaerobic methane oxidation (DAMO) archaea and DAMO bacteria could be decoupled in a microbial fuel cell (MFC) that utilized methane as fuel. The results showed that the DAMO fuel cell worked successfully, although it generated an electrogenic capability of 25 mV [61]. The results also established that after 45 days of enrichment, fluorescence and hybridization showed that the archaea percentage had increased from 26.96% (inoculum) to 65.77% (electrode biofilm), while the DAMO bacteria concentration had reduced from 24.39% to 2.07%. Such results showed that the MFC was an effective solution to separate DAMO bacteria from DAMO archaea and generate electricity from methane. Chen and Smith [62] further constructed a single-chamber and dual-chamber MFC, both of which were operated continuously on a synthetic methane-saturated medium at 20 °C with four hydraulic tensions at 4 h, 8 h, and 16 h [62]. The cell removed up to 85% of the dissolved methane and generated 0.55 ± 0.06 V of electricity. The results confirmed that MFCs recovered energy and mitigated dissolved methane emissions from anaerobic effluents [62]. Myung et al. [63] further argued that MFCs that relied on methane were not effective due to their low power density. Therefore, a strategy was employed to increase its power density, where the methane was converted to methanol, and electricity was generated using the substrate [63]. The generated results showed that methanol generated a maximum power density of 426 ± 17 mW/m^2.

3.3.2. Biogas Dry Reforming

In addition to the MFCs, a further feasible technology regards dry biogas reforming, whereby biogas containing methane is transformed into a mixture of hydrogen and carbon monoxide (syngas) through a reaction with solid catalysts at high temperatures such as 900 °C and without the presence of oxygen [64]. Nishimura et al. [64] postulated that biogas comprises CH_4 at 55–75% and CO_2 at 25–45% volume, which can be converted into hydrogen and carbon monoxide while simultaneously releasing heat energy that can also be used to power different operations in the livestock farms. In their study, [64] developed a membrane reactor to facilitate dry biogas reforming, where the effect of the pressure of sweep gas (p_{sweep}) on the process was examined. The generated findings revealed that the p_{sweep} had a small impact on hydrogen and carbon monoxide concentration following the increased reaction temperature. However, the decrease in p_{sweep} led to reduced hydrogen concentration at the outlet of the membrane reactor chamber [64]. A further finding was that the highest hydrogen concentration was generated where the molar ratio of methane to carbon dioxide was 1:1 CH_4: CO_2 = 1:1. The findings also showed that the concentration of CO was highest where the molar ratio of CH_4: CO_2 = 1.5:1 [64]. Based on the narrow scope of the research on the conversion of methane from livestock agriculture into energy, the key insight identified regards the need to ensure that the methane to carbon dioxide ratio is maintained at 1:1 in order to generate a high concentration of hydrogen gas that can be used in generating electricity. Further insights show that special membrane chamber reactors are required to undertake the conversion processes of methane to heat and hydrogen used in fuel cells that produce electricity. Likewise, the use of Ni catalysts is identified in order to transform the biogas into hydrogen through dry reforming. Figure 8 details the reactor used to convert methane into syngas [64].

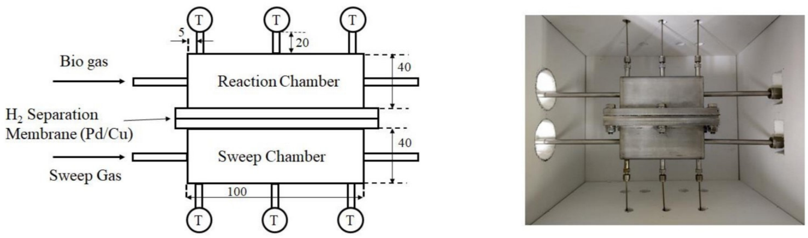

Figure 8. Schematic diagram of a reactor used in dry reforming biogas [64].

Figure 8 shows the reactor used in the dry reforming of biogas where the sweep gas and biogas were the main inputs.

Chaghouri et al. [65] further investigated how impurities affected biogas valorization through the dry reforming of methane reaction using a gas chromatography process. The study considered landfill biogas which comprises similar constituents—CH_4 and CO_2 at the highest concentrations (60%). The study further utilized CoNiMgAl catalysts that were placed in diverse conditions—toluene, water, and a combination of both. The findings revealed that the catalytic activity of the CoNiMgAl increased in the presence of toluene, although it led to the higher deposition of carbon compounds [65]. Further results showed that adding water decreased the concentrations of CO_2 and carbon formation, while also increasing the H_2/CO to values to closer to 1 [65].

The analysis of [64,65] established similar findings, where nickel-based catalysts were used to enhance the conversion of methane to syngas. Differences, however, emerged in the conversion processes employed, where [64] developed a membrane reactor, while [65] used gas chromatography. Despite such differences, it was observed that dry gas reforming could still occur in the presence of impurities, including toluene and steam, which exerted an antagonistic effect on the accumulation of carbon in the particular process.

In another study, Georgiadis et al. [66] prepared different Ni/LnO_x-type catalysts, which included LNO, CNO, SNO, and PNO, using the sol-gel method, and further utilized them in the dry gas reforming of biogas. The generated results showed that LNO possessed higher catalytic activity as compared to other types of materials, while it also generated stability followed by a drop in high-pressure due to blockage of the reactor [66]. As such, the use of a Sm catalyst in Ni/Sm_2O_3 was considered an appropriate alternative to restrict the deactivation of the catalyst [66]. Durán et al. [67] further considered a two-zoned fluidized bed reactor based on permselective membranes to generate pure hydrogen from biogas. The argument for adopting the membranes was that the reforming process was challenged by limitations that included endothermicity and catalyst deactivation by coke or the deposition of carbon [67]. To address these challenges, the study advocated for two-zone fluidized bed reactors that coupled permselective Pd/Ag membranes that counteracted them and enhanced the intensification of the process to obtain stable pure hydrogen production. The research by Durán et al. [67] is important, as it examined the impact of diverse operational variables on the yield of hydrogen and process stability. The variables comprised temperature, the height of the bed, the nature and partial pressure of the regenerative agent, and the height of the reaction zones and regeneration zones, as well as the use of activation periods. Findings from the study showed that there were over-yields of hydrogen in the range of +200% to +100% obtained in the interval temperatures between 475 to 575 °C [67]. A further finding was that catalysts were continuously regenerated, while 70% of pure hydrogen was from the permeate side of the membranes. The conclusions from the research indicated that the reactor configuration increased the conversion of methane and selectivity to hydrogen, indicated by the H_2/CO ratio in alignment with other literature results and conventional reactor findings. Therefore, relying on fluidized bed reactors based on permselective membranes enhanced the generation of pure hydrogen from up to 70% pure biogas. However, the operational temperatures and the complexity of setting up the technology may hinder its adoption in average livestock agriculture farms.

Chein and Yang [68] also conducted an experiment to demonstrate the dry reforming of biogas into syngas by utilizing Ni-based catalysts that included Ni/Al_2O_3, Pt/Al_2O_3, and Pt-Ni/Al_2O_3. The experiment also investigated the effect of CO_2 content in biogas and the addition of H_2O on dry biogas reforming under temperature conditions of 600–800 °C. Findings from the study showed that the Pt-Ni/Al_2O_3 demonstrated the highest thermal stability and best activity based on its better resistance to carbon deposition [68]. Additionally, insights showed that the conversion of CH_4 into hydrogen was enhanced, as more CO_2 content was enriched in the biogas [68]. Interesting results were also found, whereby 100% CO_2 conversion was reached where biogas contained a smaller amount of CO_2 under conditions of high temperatures, whereas adding H_2O led to steam reforming processes where there were higher H_2 and CO yields [68]. Under the steam reforming processes, the results demonstrated that lower H_2 and CO yields were obtained based on the lower SRM dominance. The addition of H_2O in dry gas reforming involving biogas led to an H_2/CO ratio with a value greater than 1, with a molar ratio of $CH_4/CO_2/H_2O$ = 1:0.25:1 at a reaction temperature of 800 °C [68].

The analysis of Georgiadis et al. [66] and Chein and Yang [68] indicated that Ni-based catalysts were highly effective in dry gas reforming where CH_4 was converted into syngas. Similar parallels were identified with [65], where the addition of H_2O increased the H_2/CO to values closer to 1. Therefore, H_2O catalyzed the dry reforming process and resulted in better H_2 yields from the biogas. Such insights are important in enhancing the dry reforming of biogas processes in order to generate high yields of H_2 that can be suitably used in fuel cells to produce energy.

Finally, Vo et al. [69] utilized simulated biogas dry reforming to generate syngas where different calcium- and cobalt-based catalysts were compared. The research considered an equal mole ratio of CH_4: CO_2 = 1:1. The goal of the research was to investigate whether calcium loading had an impact on the performance of the catalysts [69]. The generated results showed that where low calcium dosages were used in a range of 0.1–0.2 wt%, the size of the Co_3O_4 crystalline decreased from 8.15 nm to 6.01–7.43 nm. Additionally, the reducibility and basicity of catalysts were improved by adding promoters. Further analysis showed that the optimal catalysts identified regarded the 0.2Ca-10Co/Al_2O_3, which generated 84% CH_4 and 89% CO_2 conversions. The conclusion from the research by Vo et al. [69] is that earth-abundant catalysts could also be used as alternatives to the traditional Ni-based versions that were used in studies such as [66,68]. Furthermore, the calcium- and cobalt-based catalysts were identified to generate effective conversions of methane at 84% and carbon dioxide at 89%.

3.3.3. Biogas Steam Methane Reforming

The third method regards steam methane reforming, whereby methane is heated in the presence of steam and a catalyst, unlike the dry reforming process used to generate syngas [70]. In their research, Iulianelli et al. [70] considered both commercial and non-commercial membrane reactors and synthetic biogas streams that had impurities—200 ppm of H_2S. The non-commercial membrane reactors included Pd–Au/Al_2O_3 and Rh (1%)/$MgAl_2O_4$/Al_2O_3 (thickness 7–8 μm) at 873 K and 150 kPa for the sustainable generation of H_2 through the steam reforming of biogas. The generated results showed that the systems were able to recover up to 80% of the total hydrogen that was generated, and further demonstrated good resistance to contamination by H_2S. However, when the reaction was undertaken in a commercial self-supported Pd-Ag membrane with a thickness of 150 μm, the hydrogen yield was only 40% at 623 K and 200 kPa, which was affected by H_2S contamination. The conclusion was that the steam reforming process was effective in non-commercial reactors that had small wall thicknesses.

Madeira et al. [71] also used steam reforming and water gas shift to generate hydrogen from biogas sourced from swine manure. The research further computed efficiencies based on ecological, energetic, and economic aspects, where the results showed values of 93.73%, 19.15%, and 79.06%, respectively [71]. Further economic analysis established that the system had an 8-year payback period where hydrogen production costs were $0.14 kWh, with a production scenario of 8760 h/year and an exergetic efficiency of 76%. Such conclusions emphasized the economic potential of relying on hydrogen production technologies [71]. Park et al. [72] also developed a system to generate hydrogen from food waste based on anaerobic digestion conditions and biogas steam reforming. The results indicated that the shape of the reactors used impacted how the anaerobic digestion reactors performed [72]. From the findings, cubical-shaped and hydrofoil-based agitators had significant performances based on aspects such as enhanced axial flows and turbulence confirmed by computational fluid dynamics [72]. After testing the stability of the digestors for 60 days, 84 L of biogas was produced, with results showing that factors such as the steam/methane ratio and reaction temperatures affected the reactions. The optimal reaction conditions included a temperature of 700 °C and an H_2O/CH_4 ratio of 1.0. The synthesis of [71,72] showed that steam reforming could convert biogas from anaerobic digesters that processed different types of waste, including swine manure and food waste. Important insights from [72] were also identified, where the shape of reactors had an impact on the performance of the hydrogen generation from methane.

3.3.4. Other Techniques

The review has established three key techniques that are useful in the conversion of CH_4 into heat and electrical energy directly from livestock waste: the use of microbial fuel cells, the conversion of methane through dry reforming, and the steam reforming of biogas in the presence of catalysts. A fourth technology regards the combination of the steam and dry methane reforming processes to convert the methane from biogas into energy [73]. In this process, a catalytic bed was used to produce syngas with a H_2/CO ratio of 2 from directly processable methanol. The generated results emphasized that combining the steam and dry reforming processes using clean biogas generated heat and hydrogen that could be used in electricity production [74]. In turn, the process led to less environmental burden and the subsequent attainment of sustainable development.

A fifth method regards auto thermal Chemical Looping Reforming (CLRa), which involves the conversion of methane into syngas through partial oxidation and controlling oxygen flow in the fuel reactor [74]. The process considered steam reforming to generate blue H_2 from natural gas and CO_2 in biogas to produce green H_2. The synthetic Cu-based oxygen carrier was identified as an effective solution to facilitate the conversion of methane to yield H_2 parameters of 96% and 2.6 mol of H_2 per mole of CH_4. The positive results emphasized the effectiveness of Cu-based oxygen carriers as alternatives to Ni-based catalysts when producing blue and green H_2 in the CLRa process [74]. Such findings align with previous studies such as that of Vo et al. [69], who established that earth-abundant catalysts could be used as alternatives to Ni-based catalysts in biogas reforming processes.

4. Discussion

4.1. Addressing the Research Objectives

The first objective focused on the evaluation of technologies that were currently employed to capture greenhouse gases from livestock agriculture. The synthesis of the findings emphasized that animal-based techniques were the most popular and were also more diversified in addressing the particular problem. The analysis of direct gas exchange measurement methods reveals that two alternatives can be adopted: respiration chambers and spot sampling. The reviewed studies showed that indirect calorimetry respiration chamber methods were used to measure methane from enteric fermentation processes by placing animals in confined chambers for a prolonged period of time of up to seven days [25].

The further synthesis of [26,27] revealed that open-circuit respiration chambers could also be used to measure methane from different animals, including heifers and sheep. The chambers revealed the impact of feeding the animals different types of feed, such as wheat and straws, in order to examine whether the methane concentration was affected [27]. The finding is important, since it indicates the relevance of open-circuit respiration chambers in measuring the levels of methane emitted from the enteric fermentation of different animals. The synthesis of [28–30] establishes important insights regarding the level of agreement between respiration chambers and other techniques used in the measurement of methane from enteric fermentation. In [28], a comparable agreement was established between the laser methane detector (LMD) and the open-circuit respiration calorimetric chambers. In [29], a comparison was made between the open-circuit respiration chambers and a micrometeorological method, while in [30], a comparison was made against the greenfeed emission monitoring system. In the diverse studies, important findings demonstrated that open-circuit respiration chambers generated similar results as other standard techniques employed to achieve similar results. The analysis of the respiration chambers as a direct-gas measurement method indicates that the open-circuit alternative is more popular than the closed-circuit approach, as most scholars have adopted the method. Additionally, the level of agreement between the respiration chambers and other methods used in measuring methane has emphasized the novelty of the method and its significance in the current debate.

The review also investigated the spot sampling of direct-gas measurement methods to measure the levels of methane from the animals' breath over time [24]. Such insights indicate that spot sampling methods are more popular in measuring methane at a smaller scale, or from individual animals, compared to the respiration chambers where the herds are placed together. The review of the spot sampling studies [31–35] revealed that there were diverse techniques available that could capture methane from the breath of ruminants, including portable accumulation chambers (PAC), hand-held laser methane detectors (LMD), Greenfeed systems (GF), non-infrared breath analyzers (sniffers), and headbox respiration chambers. Such insights indicate that the research area is widely advanced, and that novel innovations have emerged that capture methane from the breath of the ruminants that are released from enteric fermentation.

We then considered the performance of these spot sampling measurement techniques when measuring methane from the breath of the ruminants. In [31], the results demonstrated comparable findings from PAC and respiration chamber techniques, while [33] showed that hand-held laser methane detectors (LMD), Greenfeed systems (GF), and non-infrared breath analyzers (sniffers) all ranked the ruminants similarly in measuring methane levels. In [35], a difference emerged in the LMD and sniffer methods, where the sniffer scored better. Therefore, in some instances, spot sampling methods are not interchangeable with one another, as their effectiveness in methane measurement varies.

Tracer techniques were also examined in the review, where they were associated with a major advantage of measuring methane emissions without confining the animals to either chambers or headboxes [25]. A brief synthesis of the studies involving tracer techniques showed that the SF_6 technique was widely adopted in outdoor settings, and was unaffected by rainfall or temperature and windspeed conditions [36]. The synthesis of [37] also showed that the SF_6 technique generated comparable findings to the open-circuit respiration chambers.

Finally, laser-based techniques were examined in the review paper, where they were broadly categorized into two: the hand-held laser methane detector (LMD) and the open-path laser method [39]. The LMD technique was previously discussed under spot sampling methods, where methane was measured along the beam length of the animal's nostrils. However, the analysis showed that open-path laser methods were more suitable on a large scale, where animals were grazed on large tracks of land [40]. The discussion on the open-path laser techniques in [41,42] indicated that there were differences observed in small-scale methane measurement from goats and cattle where the animals could be restrained or allowed to roam freely.

The discussion on the animal-based techniques employed for the measurement of methane generated by enteric fermentation established that the most popular involved the open-circuit respiration chambers, where animals had to be confined in seclusion with a view to measuring levels of methane generated over a period of time. However, where farmers were interested in assessing methane levels from the animals on a smaller scale, other methods, such as spot sampling, could be adopted to measure methane from the breath of the ruminants. In other cases, tracer techniques and laser-based methods could be used where the animals were herded outdoors. Such insights are illustrative of the diversity of methods available for the farmers to measure methane from livestock.

This review paper examined facility-based methods to capture and measure methane from the animals, where the main approach identified regarded the anaerobic digesters that captured methane from livestock waste [43]. The synthesis of studies such as [43–45] established that the anaerobic digesters could be adopted to capture methane from different kinds of livestock waste, including pig and cattle slurry. Based on the widespread adoption of anaerobic digesters in generating biogas in human waste and sewage treatment facilities, the method was underscored as a popular technique that most small-and-large-scale farmers would implement to capture methane.

To further advance the research area, the review paper also identified emerging methods that are being adopted to measure methane from ruminants, including blood CH_4 concentration tracers [39], IR thermography [48], intraruminal telemetry [49], eddy covariance [50,51], and carbon dioxide as a tracer gas [75]. While these methods are important based on the scope of the research, it is important to emphasize that the first research objective mainly identified open-circuit chambers and anaerobic digesters as the main methods used in capturing methane from the ruminants.

The second research objective in the review regarded the investigation of the technological innovations employed to transform greenhouse gases from livestock agriculture into energy. Addressing this objective was pivotal in the study, as the research is focused on identifying advancements regarding the transformation of greenhouse gases into different forms of energy. The main assumption held was that most livestock farmers relied on anaerobic digesters to capture methane from livestock waste, since such tools were already available in the market and could be installed on their farms. This assumption was important due to the complexities associated with the measurement of methane from animals using different available techniques.

From the findings, the conventional approach in converting biogas from livestock waste into energy was through its combustion in prime movers such as diesel engines, Stirling engines, and Otto cycle engines [53]. However, further discussion established that biogas combustion generated heat that could affect power engines and, subsequently, generators which generated electricity [54]. Additionally, the heat could be used to boil water and generate steam that could also power the generators that produced electricity. Therefore, seeking out alternatives to transform methane from biogas into energy without combustion was a key insight from this review paper.

The discussion established five methods that were novel and which had the potential to be employed in future applications with regard to the transforming of methane from biogas into energy. One approach discussed in [58] regarded the use of microbial fuel cells, which transform chemical energy from organic matter into energy. These microorganisms included *Geobacter sulfurreducens,* which decomposed the methane and generated electrons at the cathode that were consumed by oxidizing agents [58]. As a result, an electric current was generated and stored in capacitors to be utilized in different power operations. The authors of [58–60] emphasize that the microorganisms from methane-acclimated sludge produced electrons from the acetate and converted the methane directly into a current. However, the adoption of the microbial fuel cells was challenged by a variety of issues, including how the microbes would be cultured and the need for high temperatures in the range of 650 °C to 1100 °C where the reactions took place. However, with further advancements, these microbial fuel cells could be operated at room temperature, and where the culturing processes would be simplified to ensure that the methane would be converted into electricity.

The second and third methods identified in the discussion regarded dry and steam methane reforming, which involved the conversion of methane into a mixture of hydrogen and carbon monoxide (syngas) by the reaction with solid catalysts at high temperatures [65]. A review of studies, such as that of [64,65], indicated that Ni-based catalysts were the most commonly used in the dry reforming of biogas in order to generate syngas. However, LnO_x-type catalysts were also identified in [66], Pt-Ni in [68], and calcium- and cobalt-based catalysts in [69]. The distinction with the steam reforming method was that the process was conducted in the presence of steam [71,72]. The discussion revealed that the comparison of the dry and steam reforming processes showed that H_2O molecules resulted in higher H_2 and CO yields [68]. Therefore, the role of impurities in the transformation of methane into hydrogen that would later be used in fuel cells to produce electricity was underscored. The discussion further established that when focusing on the steam reforming of biogas, there was a need to consider parameters such as the shapes of the reactors, the thickness of the walls where the cubical-shaped and hydrofoil-based agitators performed well based on aspects such as enhanced axial flows and turbulence, which was confirmed by computational fluid dynamics [72].

A fourth emerging method regarded the combination of steam and dry biogas reforming methods in order to generate syngas and liquid hydrocarbons such as methanol that could be used to generate energy and electricity [73]. An earlier analysis had indicated that the conversion of methane into methanol (liquid) increased the power density to 426 ± 17 mW/m^{2,} where the liquid was used as a substrate for the generation of electricity [63]. Therefore, the method encompassed the conversion of methane into liquid hydrocarbons using gas-to-liquid techniques such as a combination of dry and steam biogas reforming processes. The methane was important as a substrate that facilitated the generation of higher power levels.

Finally, the discussion identified the auto thermal Chemical Looping Reforming (CLRa) as the fifth method, where methane was converted into syngas through partial oxidation and oxygen control in fuel reactors [74]. However, the analysis established that the CLRa method also combined steam reforming processes to generate blue H_2, indicating that the technique integrated methods that were discussed earlier. The discussion also showed that different kinds of catalysts could be adopted in the biogas reforming processes, including Cu-based oxygen carriers and Ni-based and calcium and cobalt alternatives that were earth-abundant components.

Therefore, in addressing the third objective regarding future directions and emerging solutions that transform greenhouse gases from livestock agriculture, there has been a focus on the exploration of five main methods as alternatives to the combustion of methane from livestock agriculture. These methods that have been discussed encompass microbial fuel cells, the dry reforming of biogas, steam methane reforming, CLRa, and gas-to-liquid methods where the methane is converted into liquid hydrocarbons and later used as a source of energy. However, the adoption of these methods is challenged by diverse issues, which include the complexity of some methods, such as culturing the microbial fuel cell microorganisms, the high temperatures in dry and steam methane reforming, and the setup of reactors where steam and dry reforming processes can occur to generate the liquid hydrocarbons that can be used as the sources of energy. Furthermore, identifying appropriate catalysts that can be adopted within the methane-generation processes is underscored as an existent challenge where diverse alternatives are available. These alternatives include Ni-based, Cu-based, Pt-Ni, calcium, and cobalt. The decision to select one type of catalyst over another significantly impacts carbon deposition and the levels of H_2 generated from the different chambers where the reactions occur.

4.2. Economic and Life Cycle Assessment

The further discussion identified important insights regarding the economic impact of transitioning to the innovations utilized in the production of electricity from GHGs generated by livestock agriculture. A noteworthy finding is that significant costs are associated with implementing different technologies to capture methane from enteric fermentation. Furthermore, the complexity of setting up respiration chambers and ensuring that animals remain in these setups for the set period to generate the GHGs was highlighted [25]. Similar arguments are advanced regarding the spot sampling methods and the costs of developing customized solutions that capture methane from individual animals. The findings also established that other methods, including the SF_6 technique, were complicated and did not generate comparable results to other techniques, such as the GreenFeed. However, with the facility-based techniques, closed-chamber digesters could be purchased from vendors and installed at their premises. Therefore, economic concerns mainly regard the costs and feasibility of implementing methods to measure methane from enteric fermentation processes. Additionally, they emerge with regard to the implementation of the different innovations within the livestock farms; for instance, dry and steam reforming of methane from biogas which requires diverse catalysts [64,65]. The insights from [58] indicated that the expertise required to install microbial fuel cells was expensive and impacted the long-term economic aspects of the solutions. From introspection, the economic debate in the review encompasses aspects such as the costs of the technologies to capture and measure methane, the expenses of hiring experts to manage these processes, and the long-term payback period associated with implementing these solutions. Without in-depth assessments of the economic viability of these solutions, livestock farms would be motivated to continue using the conventional combustion of biogas.

The review also examined the debate on life cycle assessments of the technologies to transform GHGs from livestock agriculture into diverse forms of energy, including heat and electricity. The assessment reveals that while the emerging innovations focus on reducing the total emissions generated from livestock agriculture by converting them into energy, a further impact may arise due to the activities undertaken. A case in point regards methods such as microbial fuel cells [58,59] and dry and steam methane reforming [71,72], which require high operating temperatures of up to 1100 °C [60]. The debates also highlight the generation of carbon monoxide as a waste material and the expected impact of carbon emissions on livestock farms. As such, a comparative assessment of the reduction in total emissions from livestock agriculture relative to the environmental impact of these technologies is brought to the fore. Insights highlight that unless the methods result in a higher reduction of emissions relative to the heat and carbon monoxide products, the methods would not be economically and environmentally viable in the long term. Furthermore, given the surrounding livestock within these plants, assessments are important to identify whether the generated waste impacts the animals.

5. Conclusions

5.1. Study Conclusions

The main research question advanced in this review paper investigated innovations that were currently employed to capture and use greenhouse gases produced within livestock farms for energy production and the expected future directions. Based on the comprehensive review of diverse studies, it emerges that the conventional method employed in the conversion of methane into energy regards combustion. With this process, the methane gas extracted from the respiration chambers or anaerobic digesters is burned to power electricity-producing generators. In the process, heat energy is also dissipated, which can be used in undertaking other important operations within livestock farms.

This paper established that diverse emerging innovations have the potential to be integrated into the conversion of methane into different forms of energy, including heat and electricity, which can be reused in livestock farms. Heat, a by-product of the chemical processes in microbial fuel cells, dry and steam reforming, can be channeled to the livestock farms to provide heating solutions, especially in the winter seasons. The generated electricity can be further used to power different operations, including feed preparation, milking, and lighting the farms.

However, criticisms were advanced against the adoption of emerging innovations within livestock farming areas. For example, with the adoption of microbial fuel cells, high operating temperatures of up to 1100 °C to sustain the reactions at the anodes and cathodes would be detrimental to the livestock, especially where methane is extracted close to the animal sheds. Further complexities arise regarding the safety of the processes and the level of expertise required to implement dry and steam methane reforming innovations within the farms successfully. Similarly, the culturing of the microorganisms at the microbial fuel cells necessitates significant knowledge and expertise in order to achieve the same process successfully.

5.2. Recommendations

The recommendations from the review paper concern the increased uptake of novel innovations that eliminate the need to transport methane gas, which leads to the susceptibility to leaks in the process. The research recommends that more innovative ways to directly convert methane from livestock agriculture into energy, such as dry and steam reforming of biogas, ought to be tested within the livestock farms in order to generate syngas, which comprises hydrogen and carbon monoxide. The hydrogen can be utilized as hydrogen fuel cells, while the carbon monoxide gas is directly adopted by plants within the farms.

A second recommendation from this research regards the need to examine the livestock agriculture farms and identify strategies that can be implemented to ensure that the innovations are successfully implemented. Conventionally, biogas from the anaerobic digesters is transported to centralized systems, where electricity is generated by power generators. However, adopting novel innovations leads to challenges in aligning them with the current design of the farms. As such, the strategies should identify whether to locate the innovations away from the animals and how to connect the electricity generated to the farms.

5.3. Future Directions and Perspectives

The future directions and perspectives from this review paper are informed by the limitations that were experienced in developing the work. The limitations in the research mainly regarded the minimal studies conducted in the specific research area. Subsequently, there was a lack of evidence on the emerging innovations being utilized to transform GHGs from livestock farms. To address this issue, there is a need for more scholars to examine the research problem and present evidence on how these innovations, such as microbial fuel cells and methane reforming, are currently being adopted within livestock farms. The studies will provide important insights regarding the conversion of GHGs from livestock agriculture to generate the energy required to power processes such as feed management and operations of the farms.

Future work should also consider primary methods that collect data from the livestock farms, such as case studies and observations where quantitative data can be collected from the systems implemented in the specific farms. Scholars should adopt broad research approaches where quantitative data on energy generated from emerging innovations ought to be compared against those conventional methods utilizing the combustion of methane from biogas.

A further future perspective regards the conducting of follow-up studies that assess the strengths and weaknesses of adopting emerging innovations to convert methane from biogas into energy. The studies should examine the health and safety effects that arise from the decision to implement the innovations within the livestock farming settings. Additionally, specific customizations that are necessary in order to adapt the innovations to livestock farming are advocated in future works.

The research presented important insights into how technologies can be integrated at the production phase by transforming methane into heat and electric energy. However, there is a need to further examine the life-cycle assessment regarding the production of energy using these innovations. Such debates will offer important insights on the impact assessment of adopting the technologies on the overall attainment of different objectives within livestock agriculture.

5.4. Further Research Needs

Despite the diversified insights identified from this review article, several research needs were further identified to enhance the comprehensiveness of the research. The insights from the article demonstrated that the conventional approach to convert biogas (which contains methane and nitrous oxide) into energy is through combustion to power generators. The research demonstrated that the alternatives are promising, and using microbial fuel cells to convert the methane into electrical energy was also identified using microorganisms. Dry and steam methane reforming were further underscored as novel methods to convert methane into syngas which comprises hydrogen and carbon monoxide. An important research area regards examining strategies to port these individual methods into the livestock agriculture sector, since they have been mainly used in industry where natural gas is concerned. Additionally, there is a need to examine whether hybrid alternatives can be adopted, for example, in combining the conventional biogas and microbial fuel cells within livestock farms. More research is required to demonstrate how average livestock farms can embrace the innovations and replace biogas combustion with the proposed alternatives. Life-cycle assessment studies are also important in understanding the long-term impact of adopting the innovations as a replacement for electricity generators.

Author Contributions: Conceptualization, C.M.; methodology, formal analysis, investigation, writing—original draft preparation, C.M.; review and editing, E.S., D.L., K.G.A., T.B. and M.I.K.; supervision, C.M. and K.G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No data available.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A. Literature Matrix

Number	Authors	Title	Methodology	Findings	Recommendation
1	[25] P. C. Garnsworthy et al.	Comparison of Methods to Measure Methane for Use in Genetic Evaluation of Dairy Cattle	Quantitative comparison of respiration chambers, SF6, breath sampling during milking and feeding, greenfeed and laser methane detector	The respiration chamber indirect calorimetry technique is the gold standard method used in the measurement of enteric methane from ruminants where the animal is confined in a chamber for 2 to 7 days. Breath sampling generated high throughput.	Use of respiration chambers to measure methane from ruminants
2	[26] J. C. Ku-Vera et al.	Determination of methane yield in cattle fed tropical grasses as measured in open-circuit respiration chambers	66 individual determinations of dry matter intake (DMI) and 42 determinations of organic matter intake (OMI) for enteric methane production	An average intake of 8.22 kg DM and 7.8 kg OM was also recorded for the heifers with the open-circuit gas exchange measurement, revealing an average CH_4 of 88 g per heifer on a daily basis	Open-circuit respiration chambers were reliable in measuring CH_4 from cattle fed tropical grasses.
3	[27] Blümmel et al.	Comparison of methane produced by straw fed sheep in open-circuit respiration with methane predicted by fermentation characteristics measured by an in vitro gas procedure	Comparison of feed intake, digestibility, and methane production by open-circuit respiration measurements in 15 sheep fed untreated, sodium hydroxide (NaOH) treated and anhydrous ammonia (NH_3) treated wheat, barley, and oat straws	Daily methane production from the open-circuit respiration chambers compared well with that from the in vitro fermentation features	Adopt open-circuit respiration chambers to measure methane from animals compared to in vitro techniques.
4	[28] M. G. G. Chagunda and T. Yan	Do methane measurements from a laser detector and an indirect open-circuit respiration calorimetric chamber agree sufficiently?	Pearson correlation and analysis of agreement based on the Bland and Altman methodology to test the laser methane detector (LMD) and the indirect open-circuit respiration calorimetric chamber	The two methods compared well against each other given the close inverse regression estimates and high correlation coefficients in the different techniques. The LMD generated higher numerical methane measurements as compared to the open-circuit respiration chambers	Both LMD and open-circuit chambers generate effective measurements of methane from ruminants

Number	Authors	Title	Methodology	Findings	Recommendation
5	[29] N. W. Tomkins, S. M. McGinn, D. A. Turner, and E. Charmley	Comparison of open-circuit respiration chambers with a micrometeorological method for determining methane emissions from beef cattle grazing a tropical pasture	Quantify CH_4 emissions from beef cattle at herd scale and from individual animals using open circuit respiration chambers and an open-path laser	Using the micrometeorological method led to comparable methane quantities to those from the open-circuit chamber method—29.7 ± 3.70 g/kg dry matter (DM) vs. 30.1 ± 2.19 g/kg, respectively	Open-circuit chambers generated comparable results to micrometeorological methods
6	[30] B. Suybeng et al.	Response to Climate Change: Evaluation of Methane Emissions in Northern Australian Beef Cattle on a High-Quality Diet Supplemented with Desmanthus Using Open-Circuit Respiration Chambers and GreenFeed Emission Monitoring Systems	Experiment 1: sixteen yearling Brangus steers fed a basal diet of Rhodes grass (Chloris gayana) hay in four treatments; the three Desmanthus cultivars and lucerne (Medicago sativa) at 30% dry matter intake (DMI) Experiment 2—GEM utilized forty-eight animals allocated to four treatments including a basal diet of Rhodes grass hay plus the three Desmanthus cultivars in equal proportions at 0%, 15%, 30% and 45% DMI.	There were no differences between the levels of methane measured using the different techniques	Open-circuit respiration chambers and GreenFeed emission monitoring systems generated comparable results regarding methane measurement
7	[31] A. Jonker et al.,	Genetic parameters of methane emissions determined using portable accumulation chambers in lambs' and ewes' grazing pasture and genetic correlations with emissions determined in respiration chambers	Quantitative measurement of CH_4 and carbon dioxide (CO_2) emissions using several 1-h portable accumulation chamber (PAC) measurements from lambs and again as ewes while grazing ryegrass-based pastures	The methane/methane + carbon dioxide ratio was comparable to the PAC and respiration chamber techniques	Open-circuit respiration chambers and PAC Systems generated comparable results regarding methane measurement

Number	Authors	Title	Methodology	Findings	Recommendation
8	[32] G. F. Difford et al.	Ranking cows' methane emissions under commercial conditions with sniffers versus respiration chambers	20 lactating dairy cows (10 Holstein and 10 Jerseys were recorded using sniffers installed in milking robots for three weeks of lactation and subsequently in respiration chambers (RC) where they were each recorded on three occasions within the RC	High correlation between methane produced from sniffers and respiration chambers: 0.77 ± 0.18 vs. 0.75 ± 0.20, respectively	Sniffers both on the farm and in respiration chambers had a potential for the measurement of methane emissions from large-scale dairy cattle
9	[33] D. Sorg et al.	Comparison of a laser methane detector with the GreenFeed and two breath analyzers for on-farm measurements of methane emissions from dairy cows	Data obtained with a handheld laser methane detector (LMD) and the GreenFeed system (GF), as well as data obtained with LMD and Fourier Transformed Infrared (FTIR) and Non-dispersive Infrared (NDIR) breath analyzers (sniffers) installed in the feed bin of automatic milking systems.	The different spot sampling devices were able to measure methane emissions on a daily basis, as a strong repeated measures correlation of LMD and GF was reported at 0.66	Different spot sampling methods ranked the cows similarly, which implied that comparable results were generated
10	[34] O. A. Castelán Ortega et al.	Construction and Operation of a Respiration Chamber of the Head-Box Type for Methane Measurement from Cattle	Six assays were conducted to determine the pure CH_4 recovery rate of the whole system in order to validate it and comply with the standards of chamber operation	Methane yields obtained from the cows and heifers: 19.7 ± 3.4 g and 17.1 ± 3.4 g CH_4 kg^{-1} of dry matter were comparable to those from the literature	Head box chambers generated comparable methane measurements to the literature
11	[35] J. Rey et al.	Comparison Between Non-Invasive Methane Measurement Techniques in Cattle	Tests were conducted between the non-dispersive infrared methane analyzer (NDIR) method and the hand-held laser methane detector (LMD). Methane (CH_4) was measured simultaneously with the two devices totaling 164 paired measurements.	There was higher methane concentration with the NDIR sniffer (0.42) as compared to the LMD (0.23)	The LMD and NDIR were not interchangeable, as they captured methane levels differently when used in livestock farms

Number	Authors	Title	Methodology	Findings	Recommendation
12	[36] P. J. Moate et al.	Measurement of Enteric Methane Emissions by the SF6 Technique Is Not Affected by Ambient Weather Conditions	Six different cohorts of dairy cows (40 per cohort) were kept outdoors and fed a common diet during spring in 3 consecutive years. Methane production from individual cows was measured daily over the last 5 days of each 32 day period. An automated weather station measured air temperature, wind speed, relative humidity, and rainfall every 10 min.	Use of the SF6 technique was feasible in outdoor settings where there were varied conditions of humidity, rainfall, temperature, and wind speed.	Using the SF6 technique facilitated the measurement of methane emissions in different outdoor weather conditions
13	[37] M. Doreau, M. Arbre, Y. Rochette, C. Lascoux, M. Eugène, and C. Martin	Comparison of three methods for estimating enteric methane and carbon dioxide emission in nonlactating cows	Comparison undertaken in eight dry cows receiving a diet made of 70% hay and 30% concentrates given in limited and constant amounts, in a 15-wk experiment. Two periods in free stalls for SF6 and GF and in chambers for OC were used; in addition, SF6 was determined in chambers for one period.	Correlation coefficients for CH_4 emission and CH_4 yield were high and significant for OC and SF6, while they were not significant between OC and GF, and GF and SF6	OC and SF6 generated comparable methane emission measurements
14	[38] I. C. de F. Maciel et al.,	Could the breed composition improve performance and change the enteric methane emissions from beef cattle in a tropical intensive production system?	Steers (n = 8) from each breed composition were randomly selected in each phase to measure CH_4 production using a sulfur hexafluoride (SF6) tracer technique and DM intake (DMI) using titanium dioxide.	The NEL had less methane intensity in grazing and average daily gain as compared to the AN. The results were also indicative that breed composition did not generate an impact on the methane yield based on dry matter intake (DMI)	Crossbreeding was an effective strategy to reduce methane levels emitted per kg of meat produced

Number	Authors	Title	Methodology	Findings	Recommendation
15	[39] T. K. Flesch et al.	Methane emissions from cattle grazing under diverse conditions: An examination of field configurations appropriate for line-averaging sensors	Experimental design using an inverse dispersion method (IDM) to measure enteric methane (CH_4) emissions, and its application to 15 rather distinct cattle trials in three types of feeding situations: summer grazing, winter swath grazing, and winter feeding	There was good agreement between the IDM designs across the 15 trials and based on the consistent forage types	Open path laser techniques were feasible in scenarios where narrow paddock IDM were used, and they generated advantages such as non-interference with the animals in their natural environments
16	[40] W. Bekele, A. Guinguina, A. Zegeye, A. Simachew, and M. Ramin,	Contemporary Methods of Measuring and Estimating Methane Emission from Ruminants	Quantitative comparison of six categories of methods for measuring and estimating CH_4 emissions from ruminants	IR thermography was a non-invasive and inexpensive technique that is adopted to detect methane emissions from ruminants by assessing changes in temperature in the rumen	Use of IR thermography technique to measure methane emissions from rumen in ruminants
16	[41] K. Kang et al.	Application of a hand-held laser methane detector for measuring enteric methane emissions from cattle in intensive farming	Experiment 1 was conducted with four Hanwoo steers (584 ± 57.4 kg body weight [BW]) individually housed in metabolic cages. In experiment 2, 30 Hanwoo growing steers (343 ± 24.6 kg BW), blocked by BW, were randomly divided into three groups. Three different diets were provided to each group: high FC ratio (35:65) with low-energy concentrate (HFC-LEC), high FC ratio with high-energy concentrate (HFC-HEC), and low FC ratio (25:75) with high-energy concentrate (LFC-HEC).	the LMD method was effective in measuring methane emissions from cattle	the LMD method was effective in measuring methane emissions from cattle

Number	Authors	Title	Methodology	Findings	Recommendation
17	[42] R. Roessler and E. Schlecht	Application of the laser methane detector for measurements in freely grazing goats: impact on animals' behavior and methane emissions	LMD to assess the CH_4 concentration in air exhaled by four pasture-fed female Thuringian Forest goats when they were either expressing their natural grazing behavior or when they were manually restrained at three times of the day over five consecutive days.	Methane emissions did not vary under restraint (6.5 ppm-m) and free-roaming (6.6 ppm-m). However, higher CH_4 concentrations were established in the exhaled air from the ruminants during the afternoons as compared to morning sessions	LMD was effective in measuring methane emissions from animals
18	[48] A. B. Meireles et al.	Use of infrared thermography in an animal model as a complementary tool for monitoring the inflammatory process: a preliminary study	CFA-induced paw edema on rats (n = 5) was performed and discrepancies between animals treated or not with anti-inflammatory drugs such as triamcinolone acetonide and diclofenac sodium were analyzed.	Using infrared thermographic cameras to measure the changes in temperature on different surfaces indicated methane emissions	
19	[49] C. McSweeney	Measuring methane in the rumen under different production systems as a predictor of methane emissions	Real time data from the capsule in the rumen can be relayed via an ear tag to a remote personal computer using the public G3 network communication system. The power supply to the device enables data logging for approximately a month when the sampling rate is set at 20–30-min intervals.	Use of IR sensors and wireless networks to measure the concentration of different gases including methane, carbon dioxide and hydrogen in the rumen by utilizing intraruminal devices	Intraruminal telemetry facilitated measurement of methane gas within the rumen
20	[50] P. Prajapati and E. A. Santos	Estimating Herd-Scale Methane Emissions from Cattle in a Feedlot Using Eddy Covariance Measurements and the Carbon Dioxide Tracer Method	A closed-path EC system was used to measure CH4 and CO_2 fluxes from a feedlot in Kansas. The EC flux measurements were scaled from landscape to animal scale using footprint analyses.	There were consistent methane emissions in the CO_2 tracer method and the EC techniques with only 3% deviations being reported during dry and cold months	Use of eddy covariance was important to measure methane emissions from cattle

Number	Authors	Title	Methodology	Findings	Recommendation
21	[51] P. Dumortier et al.	Beef cattle methane emission estimation using the eddy covariance technique in combination with geolocation	Methane emissions of a grazing herd of Belgian Blue cattle were estimated per individual on the field by combining eddy covariance measurements with the geolocation of the cattle and a footprint model	The results from the method revealed an estimate of methane emissions of 220 ± 35 g CH_4 LU^{-1} day^{-1} which indicated methane emissions per livestock units per day	Eddy covariance technique in combination with geolocation was effective for methane measurement from beef cattle
22	[52] P. C. Stoy et al.	Methane efflux from an American bison herd	Measured methane and carbon dioxide fluxes from a bison herd on an enclosed pasture during daytime periods in winter using eddy covariance.	In the absence of the bison, methane emissions were negligible in the study area but were greater than zero when the bison were incorporated 0.048 ± 0.082 µmol m^{-2} s^{-1} for the mean and standard deviations	Adopt eddy covariance to measure methane emissions from bison herd
23	[75] P. Huhtanen, A. R. Bayat, P. Lund, A. L. F. Hellwing, and M. R. Weisbjerg	Short communication: Variation in feed efficiency hampers use of carbon dioxide as a tracer gas in measuring methane emissions in on-farm conditions	Data (307 cow-period observations) from two locations using the same setup for measuring CH_4 and CO_2 in respiration chambers were compiled, and observed production of CH_4 and CO_2 was compared with the equivalent predicted production using two different approaches.	An overestimation of methane emissions by 17% for the low-efficiency cows which indicated that the method favored low-efficient cows	Disparity in results identified in the use of carbon dioxide as a tracer gas in measuring methane emissions in on-farm conditions
24	[43] T. L. I. Vergote, S. Bodé, A. E. J. De Dobbelaere, J. Buysse, E. Meers, and E. I. P. Volcke	Monitoring methane and nitrous oxide emissions from digestate storage following manure mono-digestion	Quantified methane (CH_4) and nitrous oxide (N_2O) emissions from farm-scale mono-digested dairy manure by continuous monitoring in an on-site digestate storage for three months, in autumn	Generated results showed that the methane emission generated ranged from 4.6 to 14 g m^{-3} d^{-1} per day, while the nitrous oxide emission varied from 0.004 to 0.13 g m^{-3} d^{-1}. The results further indicated that total emissions of the greenhouse gases ranged between 170 and 478 g [CO_2, eq.] m^{-3} d^{-1}, where only 10% was attributed to N_2O	Use of an n-line gas phase analyzer to quantify the CH_4 and N_2O emissions from stored manure

Number	Authors	Title	Methodology	Findings	Recommendation
25	[44] N. T. Vechi, N. S. Jensen, and C. Scheutz	Methane emissions from five Danish pig farms: Mitigation strategies and inventory-estimated emissions	Methane emissions were quantified by using the tracer gas dispersion method. Farms were measured between five and eight times throughout a whole year. One of the farms housed sows and weaners (P1) and the others focused on fattening pigs (P2–P5). The farms had different manure treatment practices including biogasification (P3), acidification (P4–P5), and no manure treatment (liquid slurry) (P1–P2).	Results showed that farms that had no manure treatment and where pigs were fattened had the highest methane emission rates, while the lowest rates of methane emission were identified in farms that had acidification manure treatment.	Manure storage generates methane emissions that can be measured using the tracer gas dispersion method.
26	[45] A. Cárdenas et al.	Methane emissions from the storage of liquid dairy manure: influences of season, temperature, and storage duration	Manure from the summer and winter season was stored under controlled conditions in barrels at ambient temperature to simulate manure storage conditions. Methane emissions from the manure samples from the winter season were measured in two time periods: 0 to 69 and 0 to 139 days. For the summer storage period, the experiments covered four time periods: from 0 to 70, 0 to 138, 0 to 209, and 0 to 279 continuous days, with probing every 10 weeks.	Storing the livestock manure in a liquid form (slurry) in conditions of higher temperature and over a long duration of time maximized the total methane emissions that could be generated.	Methane emissions were generated from stored slurry that was maintained in conditions of high temperature.

Number	Authors	Title	Methodology	Findings	Recommendation
27	[46] J. E. Hilgert et al.	Methane Emissions from Livestock Slurry: Effects of Storage Temperature and Changes in Chemical Composition	Dairy and fattening pig manure samples were stored at five different temperatures (5–25 °C) for 90 days in a laboratory-scale experiment to measure the methane production. The chemical composition of the slurry samples was analyzed, and the Biochemical Methane Potential (BMP) tests were performed before and after storage.	Results showed that temperatures between 20 °C and 25 °C accounted for the highest methane emissions at a biochemical methane potential (BMP) of 69.3% and 50.3%, respectively	Temperature had an impact on methane emissions from livestock slurry
28	[47] C. Ma, L. B. Guldberg, M. J. Hansen, L. Feng, and S. O. Petersen	Frequent Export of Pig Slurry for Outside Storage Reduced Methane But Not Ammonia Emissions in Cold and Warm Seasons	The study examined CH4 and NH3 emissions from liquid pig manure (pig slurry) removed from the in-house slurry collection pits at three different frequencies, i.e., three times per week (T2.3), once per week (T7), or once after 40 days (T40, reference). The slurry from treatments T2.3 and T7 was transferred for outside storage weekly over four weeks, and slurry from treatment T40 once after 40 days, in connection with summer and winter production cycles with growing-finishing pigs. The slurry was stored in pilot-scale storage tanks with solid cover and continuous ventilation.	The frequent export of slurry to the external storage led to more ammonia emissions and lower methane emissions	To generate more methane emissions, it was important to export the slurry to external storage sites

Number	Authors	Title	Methodology	Findings	Recommendation
29	[53] M. J. B. Kabeyi and O. A. Olanrewaju	Technologies for biogas to electricity conversion	Quantitative comparison of prime movers and different technologies that could be used to generate biogas	Prime movers useful for biogas power generation included steam and gas turbines, diesel engines, otto cycle engines and Stirling engines	Performance of biogas prime movers could be enhanced where enriched biogas or biomethane could be used in place of raw biogas
30	[54] A. Yatim, A. Luthfi, and R. Chemilo	Burner Design for biogas-fueled Stirling engine for electric power generation	Experiment involving design of a Stirling engine for biogas-fueled power generation system	The system generated 5 kW capacity fueled by 165 kg/day solid waste from a local farm with a biodigester of 20 m^3. The burner provided simultaneous air preheater for lower fuel consumption leading to 37% lower consumption of fuel.	Use of Stirling engine provided flexible flue usage for power generation
31	[55] S. Abanades et al.	A conceptual review of sustainable electrical power generation from biogas	Conceptual examination of biogas-based electrical power-production systems	Use of upgraded biogas technologies increased the lower heating values of biogas by removing the pollutants. An economic analysis of the biogas-fueled systems was also undertaken	The use of upgraded biogas technologies improved electrical power production.
32	[56] U. U. R. Zia et al.,	Technological Assessment of Bio Energy Production through Livestock Waste in Azad Jammu and Kashmir (AJK)	Quantitative assessment of the production capacity of biogas technologies	More than four million tons of biomass could be treated via technologies such as bio-methane engines, gas turbines, and steam turbines to generate over 300 TWh of energy.	The use of different types of bio-methane technologies including gas turbines, steam turbines and engines led to heat and electricity generation
33	[57] H. Barzegaravval, S. E. Hosseini, M. A. Wahid, and A. Saat	Effects of fuel composition on the economic performance of biogas-based power generation systems	An experiment to study the effects of fuel composition on exergetic and economic performance of biogas-based gas turbine systems with preheaters	Changing methane content from 0.95 to 0.6 increased the cost rate of the plant by 1%. The cost of the generated electricity varied from 0.05 $kWh to 0.18 $kWh	It is important to increase methane content in biogas-based turbine systems in order to reduce total cost rates of electricity

Number	Authors	Title	Methodology	Findings	Recommendation
34	[58] R. Yamasaki, T. Maeda, and T. K. Wood	Electron carriers increase electricity production in methane microbial fuel cells that reverse methanogenesis	The reversal of methanogenesis in microbial fuel cells to produce electricity from methane through combining archaeal strains with Geobacter and methane acclimated sludge	Adding more electron carriers and changing the order of strains of the consortium led to increased power density and current density. MFCs were able to convert methane to electricity and were limited by electron carriers.	Power density and current density were comparable for any microbial fuel cells that used non-gaseous substrates or Shewanella
35	[59] M. J. McAnulty et al.	Electricity from methane by reversing methanogenesis	Experiment where a synthetic consortium was constructed that comprised of archaeal strain with Geobacter and methane acclimated sludge	The MFC operated at high Coulombic efficiency	The use of MFC is recommended to convert methane to electricity to avoid transportation
36	[60] Z. J. Ren	Microbial fuel cells: Running on gas	Experiment to create a microbial electrochemical technology platform comprised of a consortium of microorganisms	The MFC efficiently converted methane directly to current	use of MFC is recommended to convert methane to electricity
37	[61] J. Ding et al.	Decoupling of DAMO archaea from DAMO bacteria in a methane-driven microbial fuel cell	Experiment to investigate decoupling of denitrifying anaerobic methane oxidation archaea and DAMO bacteria in a MFC where methane was used as fuel	The DAMO fuel cell worked successfully but demonstrated weak electrogenic capability with around 25 mV production. After 45 days' enrichment, the sequencing and fluorescence in situ hybridization results showed the DAMO archaea percentage had increased from 26.96% (inoculum) to 65.77% (electrode biofilm), while the DAMO bacteria percentage decreased from 24.39% to 2.07%.	The MFC may be used as a potential device to separate DAMO archaea from DAMO bacteria.

Number	Authors	Title	Methodology	Findings	Recommendation
38	[62] S. Chen and A. L. Smith	Methane-driven microbial fuel cells recover energy and mitigate dissolved methane emissions from anaerobic effluents	Experiment using microbial fuel cells, single chamber MFCs, and dual-chamber MFCs to recover energy and mitigate methane emissions from anaerobic effluents	Generated results showed that up to 85% dissolved methane removal was achieved, resulting in the generation of 0.55 ± 0.06 V	Use of the MFC generated electricity from methane and reduced total emissions
39	[63] J. Myung, P. E. Saikaly, and B. E. Logan	A two-staged system to generate electricity in microbial fuel cells using methane	MFC experiment which involved a two-step strategy where methane was converted to methanol and electricity generated using the methanol	The methanol-fed MFC produced a maximum power density of 426 ± 17 mW/m^2. It was also shown that the methanol-rich medium produced from the first step can be directly supplied to the MFCs, removing the need for the purification of methanol.	The analysis demonstrated that MFCs based on methanol could generate high power
40	[64] A. Nishimura, T. Takada, S. Ohata, and M. L. Kolhe	Biogas Dry Reforming for Hydrogen through Membrane Reactor Utilizing Negative Pressure	Quantitative study involving a membrane reactor to promote biogas dry reforming	Concentrations of hydrogen and carbon monoxide increase with increasing reaction temperature. The hydrogen concentration at the outlet chamber reduced with decreasing pressure sweep. The highest concentration of hydrogen was obtained in the molar ration of CH_4:CO_2 = 1:1	To increase the conversion of methane to hydrogen gas, it was important to ensure a ratio of 1:1 for methane to carbon dioxide concentration.
41	[65] M. Chaghouri et al.	Impact of impurities on biogas valorization through dry reforming of methane reaction	Use of gas chromatography to examine biogas composition	Methane and carbon dioxide represented 60% of the composition of biogas, which led to promising results using dry reforming. Using a toluene catalyst led to a progressive increase in catalytic activity and higher carbon deposition. The addition of water decreased carbon dioxide conversion and the formation of carbon, thereby increasing the hydrogen/CO values closer to 1	Incorporate toluene catalysts to increase the conversion of methane to hydrogen from biogas

Number	Authors	Title	Methodology	Findings	Recommendation
42	[66] A. Cabello et al.	Production of hydrogen by chemical looping reforming of methane and biogas using a reactive and durable Cu-based oxygen carrier	Use of autothermal chemical looping reforming (CLRa) to evaluate the suitability of Cu-based oxygen carriers in a continuous pilot plant to produce blue and green hydrogen	The operation of 950 °C in fuel and air reactors resulted in the conversion of methane and hydrogen at 96% and 2.60 mol of hydrogen per mole of methane. The Cu-based oxygen carrier maintained mechanical integrity and chemical stability under harsh operating conditions.	The use of Cu-based oxygen carriers was considered a promising alternative to Ni-based materials to produce green and blue hydrogen through the CLRa process
43	[67] A. G. Georgiadis et al.,	Biogas dry reforming over Ni/LnOx-type catalysts (Ln = La, Ce, Sm or Pr)	Use of the sol-gel citrate method to prepare Ni/LnO-type catalysts for the dry reforming of biogas	LNO was observed to possess higher catalytic activity in comparison to other materials. The use of Sm (Ni/Sm_2O_3) was considered an alternative strategy to restrict catalyst deactivation	The use of Ni/LnO catalysts facilitated the dry reforming of biogas
44	[68] P. Durán et al.	Pure hydrogen from biogas: Intensified methane dry reforming in a two-zone fluidized bed reactor using permselective membranes	Quantitative experiment to generate stable pure hydrogen by using a fluidized bed reactor coupled with permselective Pd/Ag membranes in the dry reforming of biogas	Hydrogen over-yields compared with conventional fluidized bed reactors in the range +200% to 100% were obtained for the interval of temperatures of 475 °C to 575 °C, while the stable operation by continuous catalyst regeneration was maintained.	Use of the bed reactor increased methane conversion and selectivity to hydrogen expressed as hydrogen to CO ratio
45	[69] R. Chein and Z. Yang	Experimental Study on Dry Reforming of Biogas for Syngas Production over Ni-Based Catalysts	Experiment to produce syngas from the dry reforming of biogas using catalysts such as Ni/Al_2O_3, Pt/Al_2O_3, and Pt-Ni/Al_2O_3	The bimetallic Pt-Ni catalysts exhibit the best activity and thermal stability among the three types of catalysts due to better carbon deposition resistance. Adding H_2O to the dry biogas reforming process leads to the steam reforming of methane as the dominant reaction which results in higher hydrogen and CO yields with biogas containing lower amounts of CO_2.	Incorporating Ni-based catalysts in dry biogas reforming leads to the best conversion of methane to hydrogen

Number	Authors	Title	Methodology	Findings	Recommendation
46	[70] C.-M. Vo et al.,	Toward syngas production from simulated biogas dry reforming: Promotional effect of calcium on cobalt-based catalysts performance	Experiment to upgrade simulated biogas with equal mole ratio of methane and carbon dioxide through dry reforming over calcium promoted on cobalt-based catalysts	At low calcium dosages in a range of 0.1–0.2 wt%, the average Co_3O_4 crystalline size decreased from 8.15 nm to 6.01–7.43 nm, suggesting well-dispersed cobalt on the surface. In addition, the reducibility and basicity of catalysts were also enhanced with a sufficient addition of promoters. The optimal catalyst, 0.2Ca-10Co/Al_2O_3, exhibited the best performance, with roughly 84% and 89% of CH_4 and CO_2 conversions, respectively	The use of earth-abundant catalysts is important to enhance the dry reforming of simulated biogas
47	[71] A. Iulianelli et al.	Sustainable H_2 generation via steam reforming of biogas in membrane reactors: H2S effects on membrane performance and catalytic activity	Experiment to steam reform synthetic biogas stream which contains 200 ppm of H_2S, carried out in a non-commercial supported Pd–Au/Al_2O_3 membrane reactor (7–8 µm selective layer thickness) at 823 K and 150 kPa over a non-commercial Rh(1%)/$MgAl_2O_4$/Al_2O_3 catalyst	The developed system was able to recover 80% of total hydrogen produced during the reaction, which shows a good resistance to H2S contamination, which was confirmed by the stable conversion of methane for more than 400 h under operation.	Using the Pd–Au/Al_2O_3 membrane reactor over a non-commercial Rh(1%)/$MgAl_2O_4$/Al_2O_3 catalyst generated higher hydrogen recovery due to lower H_2S contamination
48	[72] J. G. F. Madeira et al.	Hydrogen production from swine manure biogas via steam reforming of methane (SRM) and water gas shift (WGS): An ecological, technical, and economic analysis	The utilization of steam reforming and water gas shift processes to produce hydrogen from swine manure biogas.	The ecological efficiency, pollution indicator and energy efficiency of the process were 93.73%, 19.15%, and 79.06%, respectively, showing the viability from an ecological standpoint. An 8-year payback with a hydrogen production cost of $0.14 kWh, a production scenario of 8760 per year, and exergetic efficiency of 76%.	The production of hydrogen using this approach is economical and provides a high exegetic yield.

Number	Authors	Title	Methodology	Findings	Recommendation
49	[73] M.-J. Park et al.	System optimization for effective hydrogen production via anaerobic digestion and biogas steam reforming	Experiment to test the stability of an optimized anaerobic digestion reactor over 60 days	Conditions of the reaction such as reaction temperature and steam/methane ratio had an impact on biogas steam reforming reactions.	Steam reforming biogas from anaerobic digesters was achieved for 25 h without any significant fluctuation or deactivation
50	[74] N. Schiaroli et al.	Biogas to Syngas through the Combined Steam/Dry Reforming Process: An Environmental Impact Assessment	An experiment to produce syngas from clean biogas using a combination of steam/dry reforming.	Clean biogas-to-syngas could be generated by using the reforming processes and had the potential to reduce anthropogenic impacts on the environment	The use of combined steam and dry reforming technology was effective in producing syngas from clean biogas.

Appendix B. Literature CASP Appraisal

Study	Was the Aim Stated Clearly?	Was the Quantitative Methodology Used?	Was the Research Design Suitable in This Study?	Was the Sampling of Participants Suitable in This Study?	Was the Data Collected in a Way That Addressed the Research Problem?	Is There a Positive Relationship between the Researcher and the Participants?	Have Ethical Issues Been Implemented?	Was the Data Well Analyzed?	Are the Findings Well Stated?
[25] P. C. Garnsworthy et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[26] J. C. Ku-Vera et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[27] Blümmel et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[28] M. G. G. Chagunda and T. Yan	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Study	Was the Aim Stated Clearly?	Was the Quantitative Methodology Used?	Was the Research Design Suitable in This Study?	Was the Sampling of Participants Suitable in This Study?	Was the Data Collected in a Way That Addressed the Research Problem?	Is There a Positive Relationship between the Researcher and the Participants?	Have Ethical Issues Been Implemented?	Was the Data Well Analyzed?	Are the Findings Well Stated?
[29] N. W. Tomkins et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[30] B. Suybeng et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[31] A. Jonker et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[32] G. F. Difford et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[33] D. Sorg et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[34] O. A. Castelán Ortega et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[35] J. Rey et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[36] P. J. Moate et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[37] M. Doreau et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[38] I. C. de F. Maciel et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Study	Was the Aim Stated Clearly?	Was the Quantitative Methodology Used?	Was the Research Design Suitable in This Study?	Was the Sampling of Participants Suitable in This Study?	Was the Data Collected in a Way That Addressed the Research Problem?	Is There a Positive Relationship between the Researcher and the Participants?	Have Ethical Issues Been Implemented?	Was the Data Well Analyzed?	Are the Findings Well Stated?
[39] T. K. Flesch et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[40] W. Bekele, et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[41] K. Kang et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[42] R. Roessler and E. Schlecht	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[48] A. B. Meireles et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[49] C. McSweeney	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[50] P. Prajapati and E. A. Santos	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[51] P. Dumortier et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[52] P. C. Stoy et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Study	Was the Aim Stated Clearly?	Was the Quantitative Methodology Used?	Was the Research Design Suitable in This Study?	Was the Sampling of Participants Suitable in This Study?	Was the Data Collected in a Way That Addressed the Research Problem?	Is There a Positive Relationship between the Researcher and the Participants?	Have Ethical Issues Been Implemented?	Was the Data Well Analyzed?	Are the Findings Well Stated?
[75] P. Huhtanen, A. R. et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[43] T. L. I. Vergote et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[44] N. T. Vechi, N. S. Jensen, and C. Scheutz	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[45] A. Cárdenas et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[46] J. E. Hilgert et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[47] C. Ma, L. B. Guldberg, M. J. Hansen, L. Feng, and S. O. Petersen	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[53] M. J. B. Kabeyi and O. A. Olanrewaju	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Study	**Was the Aim Stated Clearly?**	**Was the Quantitative Methodology Used?**	**Was the Research Design Suitable in This Study?**	**Was the Sampling of Participants Suitable in This Study?**	**Was the Data Collected in a Way That Addressed the Research Problem?**	**Is There a Positive Relationship between the Researcher and the Participants?**	**Have Ethical Issues Been Implemented?**	**Was the Data Well Analyzed?**	**Are the Findings Well Stated?**
[54] A. Yatim, A. Luthfi, and R. Chemilo	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[55] S. Abanades et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[56] U. U. R. Zia et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[57] H. Barzegaravval, S. E. Hosseini, M. A. Wahid, and A. Saat	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[58] R. Yamasaki, T. Maeda, and T. K. Wood	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[59] M. J. McAnulty et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[60] Z. J. Ren	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[61] J. Ding et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Study	Was the Aim Stated Clearly?	Was the Quantitative Methodology Used?	Was the Research Design Suitable in This Study?	Was the Sampling of Participants Suitable in This Study?	Was the Data Collected in a Way That Addressed the Research Problem?	Is There a Positive Relationship between the Researcher and the Participants?	Have Ethical Issues Been Implemented?	Was the Data Well Analyzed?	Are the Findings Well Stated?
[62] S. Chen and A. L. Smith	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[63] J. Myung, P. E. Saikaly, and B. E. Logan	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[64] A. Nishimura, T. Takada, S. Ohata, and M. L. Kolhe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[65] M. Chaghouri et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[66] A. Cabello et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[67] A. G. Georgiadis et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[68] P. Durán et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[69] R. Chein and Z. Yang	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Study	Was the Aim Stated Clearly?	Was the Quantitative Methodology Used?	Was the Research Design Suitable in This Study?	Was the Sampling of Participants Suitable in This Study?	Was the Data Collected in a Way That Addressed the Research Problem?	Is There a Positive Relationship between the Researcher and the Participants?	Have Ethical Issues Been Implemented?	Was the Data Well Analyzed?	Are the Findings Well Stated?
[70] C.-M. Vo et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[71] A. Iulianelli et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[72] J. G. F. Madeira et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[73] M.-J. Park et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
[74] N. Schiaroli et al.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

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