FMDB ***Transactions on Sustainable Environmental Sciences***

Addressing Methane Venting: Strategies and Implications on the Environment

Ikpe Otor Mathew[1,*], Ipeghan Otaraku[2], Akuma Oji[3], Patience Nne Ikenyiri[4]

[1,4]Department of Chemical and Petroleum Engineering, Rivers State University, Port Harcourt, Nigeria.
[2,3]Department of Chemical Engineering, University of Port Harcourt, Rivers, Nigeria.
otorikpe@yahoo.com[1], ipeghan.otaraku@uniport.edu.ng[2], akuma.oji@uniport.edu.ng[3], ikenyiri.patience@ust.edu.ng[4]

Abstract: Industrial processes, including oil and gas production, landfill operations, and agriculture, emit methane, a potent greenhouse gas. This article examined methane emissions in Rivers State's Soku, Agbada, and Oyigbo oil and gas extraction communities. The net methane emissions(mg/l) for facilities A, B, and C are 0.90, 0.28, and 1.03, respectively. The corresponding temperature rise for the host communities over the same period were 1.87 oC, 0.37 oC, and 1.16 oC, respectively. All three sites have near-neutral unstable methane dispersion using Monin-Obukhov length. This article examined new methane venting mitigation technologies and their effects on bioenergy and environmental engineering. The study analyzed existing methane venting trends in several Rivers State oil production sites and their effects on local temperature and the environment, emphasizing the necessity for adequate mitigation. This paper also examined new methane capture, use, and sequestration technologies. The article also examines methane mitigation and bioenergy industry synergies, stressing co-benefit strategies that improve sustainability and economic feasibility. Methane mitigation strategies in Rivers State increase energy efficiency, carbon footprint, and air quality, according to the paper. This study helps reduce methane emissions by providing possible alternatives and their effects on bioenergy development and environmental stewardship. Interdisciplinarity and innovation are encouraged to accelerate sustainable and resilient development.

Keywords: Bioenergy and Environment; Methane Monitoring; Methane Venting; Oil and Gas Facilities; Technological Solutions; Economic Considerations; Vapor Recovery Units (VRUs); Quality Control Measures.

Received on: 22/07/2023, **Revised on:** 27/09/2023, **Accepted on:** 19/10/2023, **Published on:** 03/03/2024

Journal Homepage: https://www.fmdbpub.com/user/journals/details/FTSESS

DOI: https://doi.org/10.69888/FTSESS.2024.000147

Cite as: I. O. Mathew, I. Otaraku, A. Oji, and P. N. Ikenyiri, "Addressing Methane Venting: Strategies and Implications on the Environment," *FMDB Transactions on Sustainable Environmental Sciences*., vol. 1, no. 1, pp. 41–56, 2024.

1. Introduction

Methane, a potent greenhouse gas, poses a significant challenge to environmental sustainability and efforts to combat climate change. While carbon dioxide often receives the most attention in discussions about greenhouse gas emissions, methane's impact cannot be overlooked. Methane, though less prevalent in the atmosphere than carbon dioxide, is approximately 25 times more effective at trapping heat over 12 years [1]. This heightened potency makes methane emissions a crucial factor in global warming and climate change mitigation strategies. Against this backdrop, methane venting emerges as a notable concern. It occurs during various industrial activities, including oil and gas extraction, coal mining, and waste management processes. These activities release methane into the atmosphere, contributing substantially to the greenhouse effect and amplifying climate change. Addressing methane venting is imperative for curbing greenhouse gas emissions and advancing environmental

*Corresponding author.

sustainability goals. Methane venting contributes significantly to the rising atmospheric temperature of the host community, leading to different inherent climate change crises. Mitigating methane venting is crucial for reducing overall greenhouse gas emissions and limiting global temperature rise [2]. Implementing strategies such as improving leak detection and repair, transitioning to cleaner energy sources, and capturing and utilizing methane are essential for addressing methane venting and promoting environmental sustainability in Rivers State. Methane leakages may not always be visible to the naked eye, especially if the release is small or occurs in a dispersed manner. In some cases, methane leakages can be detected by observing a faint shimmer or distortion in the air at the source. If the release is significant, it may manifest as a plume of gas, often colorless and odorless but sometimes accompanied by other gases that can give it a slight colour or smell. An explosion might occur only when the percentage of methane in the air is between 5% - 15% [3].

Through the help of a high-resolution infrared camera, methane leakages can be captured more clearly. Methane gas itself is invisible in the visible spectrum. Still, thermal imaging cameras can detect methane leaks by capturing the temperature difference between the gas and its surroundings, as deployed in Soku, Agbada, and Oyigbo in this study. In thermal images, methane leaks may appear as plumes of varying temperatures against the background, depending on factors like wind speed and ambient temperature. These images can help pinpoint the source of leaks and facilitate prompt mitigation efforts to reduce emissions.

Hence, for a proper understanding of methane venting/dispersion and its impact on the three communities chosen for this study, ambient air temperature, wind speed, and methane concentration for those communities were monitored over one year. The objective of this research paper is to examine the effect of Air Velocity on methane concentration, the Impact of Ambient Air temperature on methane concentration, and the combined effects of Air velocity and Ambient air temperature on methane dispersion at Facility A, B, and C located at Soku, Agbada, and Oyigbo respectively.

1.1. Current practices and Regulation of methane venting in Rivers State

Many of the policies do not go far enough to address the problem of methane venting. Many companies employ technologies such as vapour recovery units (VRUs) to capture and reuse methane that would otherwise be vented into the atmosphere. Flaring is another method employed by oil companies to reduce methane venting, and flaring is the controlled burning of methane and other hydrocarbon. Another policy regulation is the implementation of leak detection and repair (LDAR) programs. Monitoring and Reporting: this may involve conducting periodic leak detection surveys, installing continuous emissions monitoring systems (CEMS), and submitting emissions reports to regulatory agencies, which HYPREP also enforces.

1.2. Relevance of Chemical and Environmental Engineering in mitigating methane emissions

Bioenergy refers to energy derived from organic materials such as agricultural residues, crop wastes, and organic municipal waste [5]. By converting these materials into biofuels through chemical engineering processes like anaerobic digestion or biomass gasification, we can produce energy while simultaneously reducing methane emissions. Anaerobic digestion, for example, converts organic waste into biogas, which can be used for electricity generation or as a transportation fuel, thus contributing to methane emissions. Through the process of carbon sequestration, bioenergy crops such as switchgrass and willow trees can sequester carbon dioxide from the atmosphere through photosynthesis. Oil production companies should promote the cultivation of such crops and transit into bioenergy projects to mitigate methane emissions. The synergy between bioenergy production and environmental engineering provides effective strategies for mitigating methane emissions [8].

2. Review of Literature

Methane, a potent greenhouse gas, is a significant contributor to climate change. Methane venting, whether intentional or unintentional, poses environmental risks and exacerbates global warming. Addressing methane venting requires multifaceted strategies to mitigate its impact on the environment. This literature review examines various approaches and their implications for environmental conservation.

2.1. Current State of Methane Venting

Recent studies [1]; [5] reveal alarming rates of methane venting across industrial sectors, including oil and gas extraction, coal mining, and agriculture. These findings underscore the urgent need for effective mitigation strategies. They also highlighted the impact of air velocity on the dispersion of methane. In their work, they evaluated the Monin-Obuhov of $-900 \leq LMO \leq -800$, a near-neutral unstable dispersion model, meaning they needed more parameters to efficiently describe the dispersion of methane in the air.

2.2. Technological Solutions

Innovative technologies such as methane capture and utilization have gained traction as promising solutions to reduce methane emissions [2]; [6]. Advanced monitoring systems and leak detection technologies also play a crucial role in identifying and addressing sources of methane venting [9].

2.3. Policy and Regulatory Frameworks

Robust policy frameworks are essential for incentivizing emissions reductions and enforcing compliance with methane mitigation measures [4]. Recent policy initiatives, such as methane emission regulations and carbon pricing mechanisms, have demonstrated the potential to curb methane venting [1].

2.4. Economic Considerations

Economic analyses highlight the cost-effectiveness of methane mitigation measures compared to the long-term environmental and societal costs of unchecked venting [5]. Strategies that integrate economic incentives with environmental objectives can promote sustainable methane management practices [10].

2.5. Environmental Impacts and Ecological Consequences

Methane venting not only contributes to global warming but also poses risks to ecosystems and biodiversity [1]; [9]. Studies underscore the importance of considering the ecological ramifications of methane emissions in mitigation efforts [4].

2.6. Stakeholder Engagement and Collaboration

Effective mitigation of methane venting requires collaboration among stakeholders, including government agencies, industry players, and environmental advocacy groups [4]. Engaging diverse stakeholders fosters knowledge-sharing and consensus-building toward sustainable solutions [3]. Addressing methane venting is a complex challenge with far-reaching implications for the environment. By integrating technological innovation, robust policy frameworks, economic incentives, and stakeholder collaboration, effective strategies can be developed to mitigate methane emissions and safeguard the planet for future generations.

3. Materials and Methods

Three different oil facilities were chosen from three different communities, all in Rivers State, for facility and client protection, the GPS location and other specific detailed information of the Sites will not be shared in this report. Facilities A, B, and C are located in Soku, Agbada, and Oyigbo, respectively, all in Rivers State, Nigeria. Those communities were chosen because of active oil and gas extraction activities going on as well as accessibility and safety considerations for deploying monitoring equipment at each site were met.

3.1. Sampling Equipment Setup

Methane monitoring equipment (Oizom SBS-CH4), wind speed sensors (AOPUTTRIVER AP007-WB), and thermometer sensors (BRAUN IRT6525) were installed at different locations within each Site (Soku, Agbada and Oyigbo facility) and three different points at a distant of 1km from the facility for control to monitor methane leakages and dispersion as a result of the influence of wind speed and temperature. Methane detectors were placed at various heights to capture potential variations in methane concentration at different levels of the atmosphere; also, the wind speed sensors were placed in an open area away from obstructions to obtain accurate measurements of wind velocity and direction. The deployed thermometers were placed in a shaded area to minimize direct sunlight exposure and ensure accurate ambient temperature readings.

3.2. Sampling Schedule and Quality Control Measures

A monthly monitoring schedule for data collection across all the locations over one year (starting from June 2022 to June. 2023) was followed for methane emissions, wind speed, and ambient temperature. Regular calibration of monitoring equipment to maintain measurement accuracy and reliability was carried out. The result for June 2022 is compared with that of June 2023. Temperature measurements were taken at 6 a.m. to minimize the effect of the heat from the sun.

3.3. Methane Dispersion Model

The analysis of the dispersion of methane in the air for the three selected Sites is an important aspect of this paper; the Monin-Obukhov length will be used to describe the dispersion of methane in the lower tenth of the atmospheric boundary layer. The equations are shown in Eq. 1 and 2 [4].

$$L = \frac{U_*^3 T}{K_v g w^l T^l} \tag{1}$$

$$U_* = [(u^l w^l)^2 + (v^l w^l)^2]]^{\frac{1}{4}} \qquad (2)$$

Where, $L = obukhov\ length, m$, $U_* = surface\ friction\ air\ velocity, m/s$, $T = mean\ absolute\ air\ temperature, k$, $K_v = Von\ karman\ constant = 0.41$ and $g = gravitational\ acceleration = 9.81 m/s^2$.

In order to reflect the field data collection exercise, Figure 1 shows Facility A methane leakages and dispersion under the infrared camera, and Figure 2 shows Facility B's methane monitoring and dispersion under the infrared camera. In contrast, Figure 3 shows Facility C's methane monitoring.

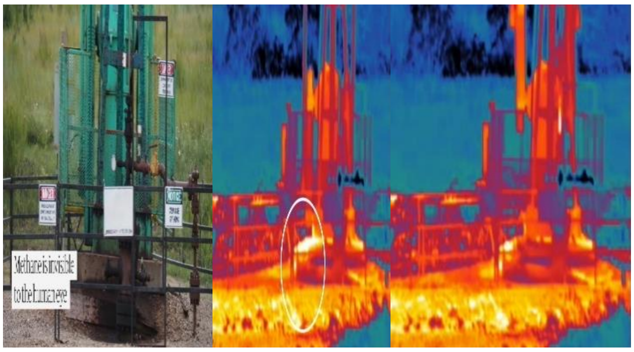

Figure 1: Facility A methane leakages and dispersion under infrared camera

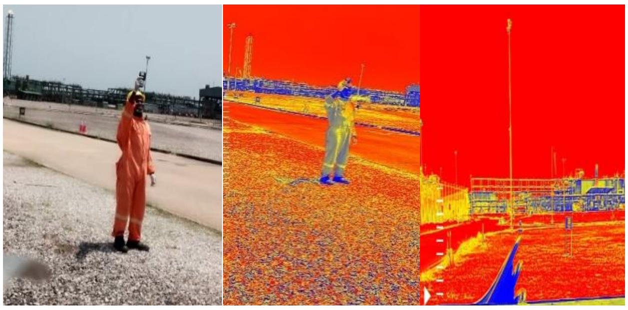

Figure 2: Facility B methane monitoring and dispersion under infrared camera

Figure 3: Facility C methane monitoring

4. Results

Throughout the research period, results for different parameters were collected and recorded. Table 1 shows methane monitoring for Facility A, and Table 2 shows methane monitoring for Facility B, while Table 3 shows methane monitoring for Facility C. It is necessary to note that Facility A is located at Soku, Facility B is located at Agbada, and Facility C is located at Oyigbo; all three facilities are situated in Rivers State. The results in Table 1 below show the parameters under consideration for Soku.

Table 1: Methane monitoring for Facility A

Season 1					Season 2			
SC	**CH_4 mg/l**	**WS m/s**	WD	**T (°C)**	**CH_4 mg/l**	**WS m/s**	WD	**T (°C)**
Q1	10	1.3	NW	29.7	19	1.3	NW	35.2
Q 2	12	0.1	SW	30.5	18	0.1	SW	31.5
Q 3	18	0.2	SW	32.1	20	0.4	SW	32.1
Q 4	17	0.1	NW	31.2	18	0.2	NW	33.2
Q 5	16	1.8	SW	29.2	16	1.7	SW	29.2
Q 6	8	2.5	SW	33.3	10	2.5	SW	33.3
Q 7	15	1.5	SW	29.9	15	1.5	SW	29.9
Q 8	9	0.5	SW	26.7	11	0.4	SW	29.7
Q 9	5	0.5	SW	34.6	8	0.5	SW	34.6
Q10	11	0.6	SW	28.2	11	0.6	SW	28.7
Q11	5	3.5	N	26.5	4	3.4	N	26.5
Q12	6	2.0	NE	32.1	6	2.1	NE	32.3
Q13	9	1.7	SW	29.7	8	1.7	SW	29.9
Q14	5	0.6	NE	31.6	3	0.6	NE	31.9
Q15	8	0.3	SW	27.6	5	0.5	SW	28.7
Q16	7	2.5	NE	32.7	13	2.5	NE	32.8
Q17	14	0.2	SW	30.4	14	0.2	SW	30.5
Q18	19	0.9	NW	30.5	20	0.9	NW	30.7
Q19	9	0.2	SW	31.5	17	0.2	SW	31.6
Q20	10	0.4	N	30.8	7	0.4	N	30.9
Q21	19	0.9	SW	29.6	19	0.9	SW	29.8
Q22	9	2.5	NE	29.9	7	2.4	NE	30.0
Q23	15	0.9	NW	28.9	18	1.9	NW	28.9
Q24	17	0.6	NW	27.1	17	0.9	NW	27.8
Q25	8	0.7	SW	28.5	9	0.8	SW	28.8
Q26	12	1.0	NE	33.1	3	1.1	NE	33.3
Q27	11	2.4	NW	26.7	11	2.4	NW	26.7
Q28	12	0.7	SW	31.1	15	0.9	SW	31.1
Q29	12	0.2	SW	24.3	12	0.1	SW	24.3
QC1	4	0.4	NW	25.7	3	0.6	NW	27.7
QC2	4	0.3	SW	24.8	1	0.4	SW	26.4
QC3	2	0.8	SW	26.6	2	0.7	SW	28.6

4.1. Increase in Methane Concentration

The increase in methane concentration from 2 mg/l to 18 mg/l indicates a substantial rise in the amount of methane present in Facility A. Higher concentrations of methane can pose safety hazards due to its flammability and potential health risks if inhaled in large quantities. The increase in methane concentration could be attributed to various factors, such as increased emissions due to leakages, reduced ventilation, or changes in production processes within Facility A.

4.1.1. Increase in Wind Speed

The increase in wind speed from 0.1 m/s to 0.2 m/s suggests a higher rate of air movement within and around Facility A. Wind plays a crucial role in dispersing pollutants in the atmosphere. Higher wind speeds facilitate the dispersion of methane by carrying it away from its source more effectively.

4.1.2. Rise in Ambient Temperature

The increase in ambient temperature from 30.5°C to 32.1°C indicates a slight but noticeable warming of the surrounding environment. Temperature influences the behaviour of gases, including methane. Warmer temperatures lead to increased volatility and higher rates of evaporation of methane from surface sources. Additionally, temperature impacts atmospheric stability, which affects the dispersion and transport of methane around the facility. Thus, the results in Table 1 indicate a complex interplay of factors influencing the behavior and dispersion of methane in Facility A's environment. Understanding these dynamics is crucial for managing and mitigating potential risks associated with methane emissions. It also underscores the importance of monitoring and controlling methane emissions to minimize environmental and safety concerns. For a pictorial representation of the dispersion of methane in Facility A, Figures 4 and 5 show the results for seasons 1 and 2.

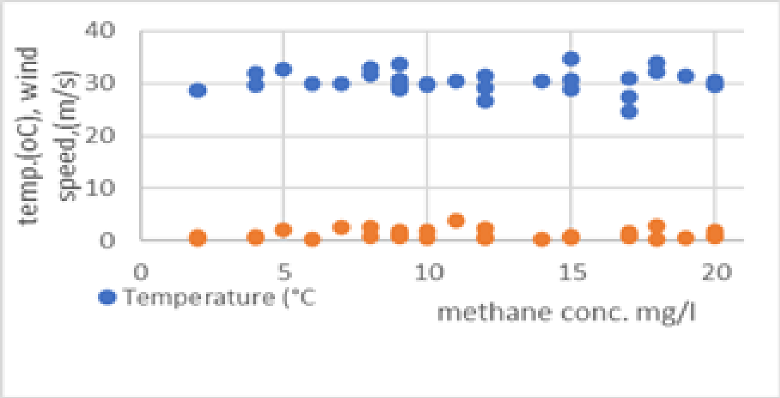

Figure 4: methane dispersion for season 1 of Facility A

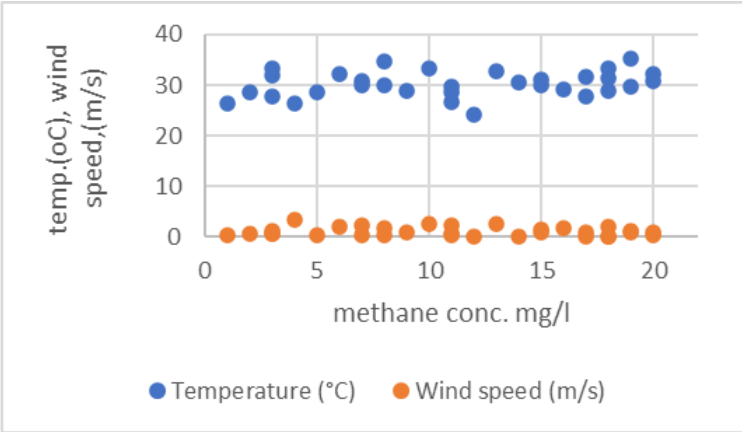

Figure 5: methane dispersion for season 2 of Facility A

The results in Table 2 below show the parameters under consideration for Agbada.

Table 2: Methane monitoring for Facility B

	Season 1				**Season 2**			
SC	**CH_4 mg/l**	**WS m/s**	WD	**T (°C)**	**CH_4 mg/l**	**WS m/s**	WD	**T (°C)**
Q1	19	1.3	NW	31.7	20	1.4	NW	30.5
Q 2	20	0.1	SW	30.5	16	0.2	SW	30.8
Q 3	19	0.2	SW	32.1	19	0.2	SW	32.9
Q 4	16	0.1	NW	31.2	21	0.3	NW	31.6
Q 5	18	1.8	SW	29.2	18	1.7	SW	29.9
Q 6	11	2.5	SW	33.3	9	2.6	SW	33.8
Q 7	16	1.5	SW	29.9	15	1.3	SW	29.9
Q 8	12	0.5	SW	26.7	12	0.6	SW	26.8
Q 9	12	0.5	SW	34.7	8	0.3	SW	34.8
Q10	11	0.6	SW	28.3	11	0.7	SW	29.2
Q11	9	3.5	N	26.7	9	3.4	N	26.6
Q12	6	2.0	NE	32.3	5	2.1	NE	32.8
Q13	9	1.7	SW	29.8	10	1.8	SW	29.7
Q14	7	0.6	NE	31.6	6	0.5	NE	31.9

Q15	8	0.3	SW	27.6	4	0.5	SW	28.6
Q16	5	2.5	NE	32.7	5	2.6	NE	32.7
Q17	14	0.2	SW	30.4	14	0.1	SW	30.5
Q18	19	0.9	NW	30.5	19	1.0	NW	30.7
Q19	7	0.2	SW	31.5	8	0.3	SW	31.9
Q20	3	0.4	N	30.8	7	0.4	N	30.9
Q21	19	0.9	SW	29.6	19	0.8	SW	29.8
Q22	8	2.5	NE	29.9	8	2.4	NE	30.9
Q23	15	0.9	NW	28.9	16	0.8	NW	28.9
Q24	17	0.6	NW	27.1	19	0.5	NW	27.7
Q25	9	0.7	SW	28.5	9	0.	SW	28.6
Q26	7	1.0	NE	33.1	14	1.1	NE	33.7
Q27	12	2.4	NW	26.7	15	2.5	NW	26.8
Q28	15	0.7	SW	31.3	14	0.8	SW	31.5
Q29	12	0.2	SW	31.3	13	0.3	SW	24.3
QC1	3	0.4	NW	28.9	2	0.5	NW	29.8
QC2	2	0.3	SW	29.8	3	0.3	SW	29.9
QC3	1	0.8	SW	29.6	3	0.9	SW	29.7

4.2. Increase in Methane Concentration

The increase in methane concentration from 19 mg/l to 20 mg/l indicates a smaller but still notable rise in the concentration of methane in Facility B compared to Facility A. While the absolute increase is less significant, any increase in methane concentration can still pose environmental and safety concerns, especially if the facility is not equipped with adequate emission control measures. The reasons behind this increase could be similar to those for Facility A, such as changes in production processes or equipment malfunctions.

4.2.1. Decrease in Wind Speed

The decrease in wind speed from 1.3 m/s to 0.1 m/s represents a substantial reduction in the rate of air movement within and around Facility B. Lower wind speeds limit the dispersion of pollutants, including methane, and can result in the accumulation of gases in the vicinity of emission sources. This reduction in wind speed could be due to various factors, including local weather conditions or changes in atmospheric pressure patterns.

4.2.2. Drop in Ambient Temperature

The decrease in ambient temperature from 31.7°C to 30.5°C indicates a slight cooling of the surrounding environment. Cooler temperatures can influence the behaviour of gases, potentially affecting the volatility and evaporation rates of methane. However, the impact of temperature on methane dispersion may be less significant compared to other factors like wind speed and concentration.

4.2.3. Implications for Methane Dispersion

The combination of a higher methane concentration, lower wind speed, and slightly cooler temperatures suggests that the dispersion of methane in Facility B may be limited compared to Facility A. Lower wind speeds hinder the movement of methane away from its source, potentially leading to localized accumulation and higher concentrations in the immediate vicinity of emission points. The decrease in temperature may have minor effects on methane dispersion compared to the dominant influence of wind speed. Hence, the data for Facility B indicates a different set of conditions compared to Facility A, with potentially lower levels of methane dispersion due to decreased wind speeds. However, even with lower dispersion, the increase in methane concentration underscores the importance of monitoring and managing emissions to mitigate environmental and safety risks. For a pictorial representation of the dispersion of methane in Facility B, Figures 6 and 7 show the results for seasons 1 and 2.

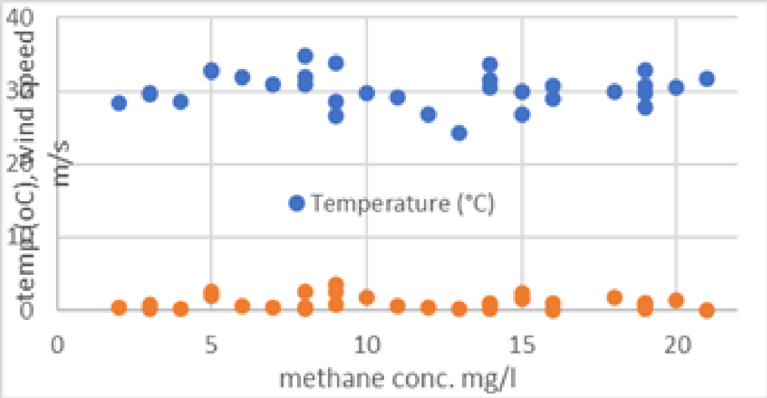

Figure 6: methane dispersion for season 1 of Facility B

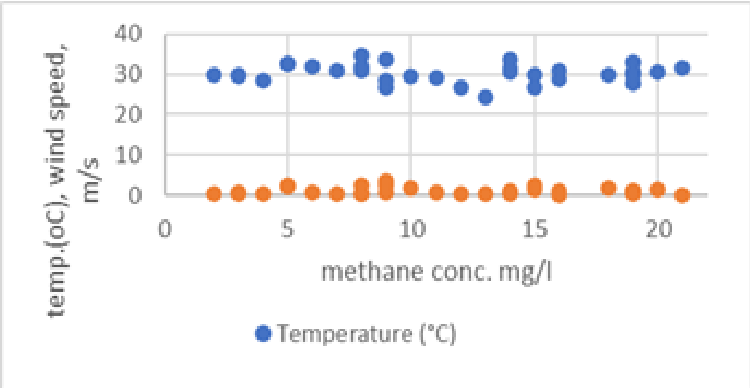

Figure 7: methane dispersion for season 2 of Facility B

The results in Table 3 below show the parameters under consideration for Oyigbo.

Table 3: Methane monitoring for Facility C

	Season 1				**Season 2**			
SC	**CH_4 mg/l**	**WS m/s**	WD	**T (°C)**	**CH_4 mg/l**	**WS m/s**	WD	**T (°C)**
Q1	14	1.4	NW	29.9	9	1.8	NW	29.8
Q 2	16	0.1	SW	30.5	14	0.2	SW	30.5
Q 3	18	0.2	SW	32.3	18	0.4	SW	32.1
Q 4	17	0.1	NW	31.4	19	0.6	NW	31.5
Q 5	16	1.8	SW	30.0	20	1.8	SW	29.8
Q 6	9	2.5	SW	33.3	18	2.8	SW	33.9
Q 7	17	1.5	SW	30.9	17	1.5	SW	30.9
Q 8	10	0.5	SW	26.9	10	0.5	SW	29.9
Q 9	8	0.5	SW	34.7	15	0.7	SW	34.6
Q10	11	0.6	SW	29.2	12	0.6	SW	29.2
Q11	6	3.5	N	26.3	11	3.8	N	30.5
Q12	5	2.0	NE	32.7	5	2.1	NE	32.8
Q13	10	1.7	SW	29.9	10	1.8	SW	29.8
Q14	6	0.6	NE	28.9	4	0.8	NE	31.9
Q15	3	0.3	SW	28.6	6	0.3	SW	29.9
Q16	4	2.5	NE	32.8	8	2.5	NE	32.9
Q17	15	0.2	SW	30.5	15	0.6	SW	30.8
Q18	19	0.9	NW	30.6	20	0.9	NW	30.4
Q19	7	0.2	SW	31.7	8	0.7	SW	31.6
Q20	3	0.4	N	30.9	9	0.8	N	30.8

Q21	19	0.9	SW	31.6	20	0.9	SW	29.8
Q22	14	2.5	NE	29.9	7	2.5	NE	29.9
Q23	15	0.9	NW	28.9	15	0.9	NW	28.9
Q24	17	0.6	NW	30.1	17	0.8	NW	27.3
Q25	8	0.7	SW	30.5	9	0.7	SW	28.9
Q26	8	1.0	NE	33.5	9	1.2	NE	33.8
Q27	11	2.4	NW	32.7	12	2.4	NW	26.6
Q28	17	0.7	SW	31.7	12	0.6	SW	31.4
Q29	13	0.2	SW	30.3	17	0.8	SW	24.6
QC1	2	0.4	NW	27.7	2	0.4	NW	28.7
QC2	2	0.3	SW	27.8	4	0.6	SW	29.8
QC3	2	0.8	SW	28.1	2	0.8	SW	28.6

4.2.4. Increase in Methane Concentration

The substantial increase in methane concentration from 3 mg/l to 19 mg/l indicates a significant rise in the amount of methane present in Facility C. This increase could be attributed to various factors such as increased emissions, changes in production processes, or equipment malfunctions. Such a significant increase in methane concentration raises environmental and safety concerns due to its flammability, potential health risks, and contribution to climate change.

4.2.5. Increase in Wind Speed

The increase in wind speed from 0.4 m/s to 0.9 m/s suggests a notable increase in the rate of air movement within and around Facility C. Higher wind speeds facilitate the dispersion of pollutants, including methane, by carrying them away from their source more effectively. This increased dispersion can help mitigate potential risks associated with high methane concentrations by reducing localized accumulations and promoting dilution in the surrounding atmosphere.

4.2.6. Rise in Ambient Temperature

The increase in ambient temperature from 30.9°C to 31.6°C indicates a slight warming of the surrounding environment. While the temperature rise is relatively small, it can still impact the behavior of gases, including methane. Warmer temperatures can increase the volatility and evaporation rates of methane, potentially affecting its dispersion. Additionally, temperature influences atmospheric stability, which can further affect the transport and dispersion of pollutants.

4.2.7. Implications for Methane Dispersion

The combination of a substantial increase in methane concentration, higher wind speed, and slightly warmer temperatures suggests that the dispersion of methane in Facility C may be more effective compared to scenarios with lower concentrations or wind speeds. The higher wind speed enhances the dispersion of methane, helping to reduce localized accumulations and promoting the dilution of methane in the surrounding air. The slight increase in temperature may further contribute to the dispersion process, albeit to a lesser extent compared to wind speed. Therefore, the data for Facility C indicates conditions conducive to more effective dispersion of methane despite the significant increase in methane concentration. However, it's crucial to continue monitoring methane emissions in this facility and implementing appropriate mitigation measures to minimize environmental and safety risks associated with elevated methane levels. For a pictorial representation of the dispersion of methane in Facility C, Figures 8 and 9 show the results for seasons 1 and 2.

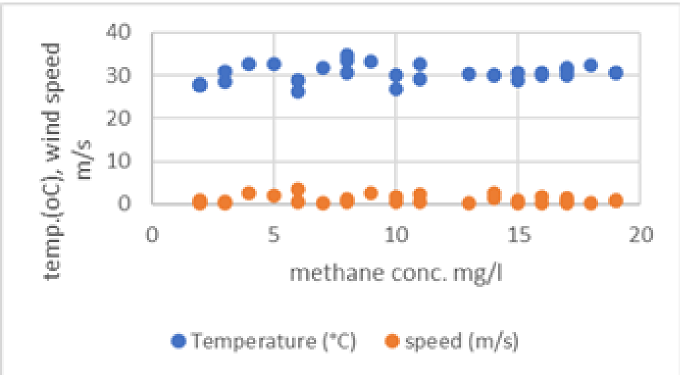

Figure 8: methane dispersion for season 1 of Facility C

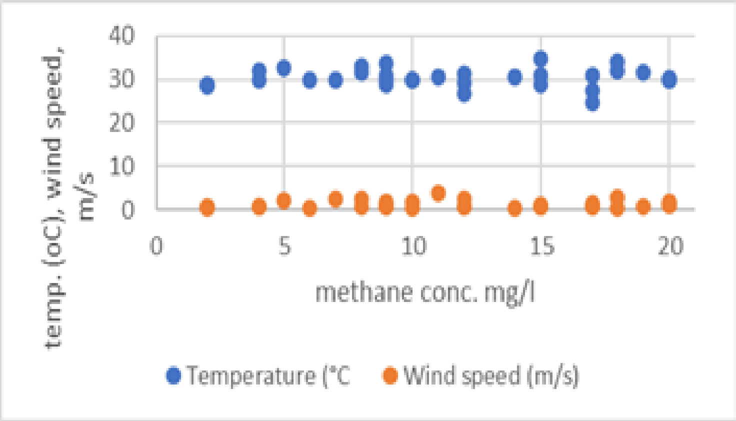

Figure 9: methane dispersion for season 2 of Facility C

In order to ascertain the stability of methane in and around the facilities, the parameters in Table 4 will be used to calculate the Monin-Obukhov length.

Table 4: Methane Dispersion and Temperature Variation

Facilities	Averages	Season 1	Season 1
Facility A	Aver. **CH_4 mg/l (within)**	11.31	12.21
	Aver. **CH_4 mg/l (control)**	3.33	2.00
	Aver. **T(°C) (within)**	29.93	30.48
	Aver. **T(°C) (control)**	25.70	27.57
Facility B	Aver. **CH_4 mg/l (within)**	12.24	12.52
	Aver. **CH_4 mg/l (control)**	2.00	2.67
	Aver. **T(°C) (within)**	30.27	30.30
	Aver. **T(°C) (control)**	29.43	29.80
Facility C	Aver. **CH_4 mg/l (within)**	11.59	12.62
	Aver. **CH_4 mg/l (control)**	2.00	2.67
	Aver. **T(°C) (within)**	30.70	30.51
	Aver. **T(°C) (control)**	27.87	29.03

Using equation 3, 4, and Table 4 above,

$$L = \frac{U_*^3 T}{K_v g w^l T^l} \quad (3)$$

$$U_* = [(u^l w^l)^2 + (v^l w^l)^2]]^{\frac{1}{4}} \quad (4)$$

Where, $L = obukhov\ length, m,$ $U_* = surface\ friction\ air\ velocity, m/s,$ $T = mean\ absolute\ air\ temperature, k,$ $K_v = Von\ karman\ constant = 0.41$ and $g = gravitational\ acceleration = 9.81 m/s^2$.

The Monin-Obukhov length for facilities A, B, and C:

$-980 \leq L_{MO} \leq -806$, $-816 \leq L_{MO} \leq -815$ and $-1256 \leq L_{MO} \leq -877$ respectively.

4.3. Implications for Environmental Management

The findings from the analysis of methane dispersion patterns in different facilities underscore the critical role of meteorological factors such as air velocity and temperature in environmental management and methane mitigation strategies. Here are some implications of these findings:

4.3.1. Understanding Dispersion Patterns

The analysis highlights how variations in air velocity and temperature can significantly influence the dispersion patterns of methane emissions in the three facilities, as shown in Figures 4 to 9. Higher wind speeds promote more effective dispersion of methane by carrying it away from its source, while lower wind speeds lead to localized accumulations and higher concentrations near emission points. Additionally, changes in temperature can impact the volatility and evaporation rates of methane, further influencing its dispersion behavior.

4.3.2. Importance of Real-Time Monitoring

Real-time monitoring of meteorological conditions, including air velocity and temperature, is essential for accurately predicting methane dispersion patterns and assessing potential risks to the environment and human health. Continuous monitoring allows for the timely detection of changes in atmospheric conditions that may affect methane dispersion, enabling proactive mitigation measures to be implemented.

4.3.3. Designing Effective Emission Control Measures

Effective emission control measures for methane must take into account not only the characteristics of the emission source but also the surrounding meteorological conditions. For example, in Facility A, B, and C, with high methane emissions, strategies such as improved ventilation systems or emission capture technologies may be more effective in conjunction with higher wind speeds that facilitate dispersion. Conversely, in environments with low wind speeds, additional measures such as enhanced containment or reduction of emission sources may be necessary to prevent localized accumulations of methane.

4.3.4. Dynamic Modeling Efforts

Dynamic modeling efforts that incorporate real-time meteorological data are essential for accurately predicting methane dispersion patterns and evaluating the effectiveness of emission control measures. These models can simulate the complex interactions between methane emissions, atmospheric conditions, and terrain features, providing valuable insights for environmental management decision-making including the plant operators. By accounting for dynamic atmospheric conditions, such as changes in wind speed, wind direction, and temperature, these models can help optimize the design and implementation of methane mitigation strategies. Therefore, considering meteorological factors such as air velocity, wind direction, and temperature is crucial for predicting methane dispersion patterns and designing effective emission control measures. Real-time monitoring and dynamic modeling efforts play a key role in assessing environmental risks associated with methane venting and informing decision-making processes for methane mitigation strategies. By integrating meteorological data into environmental management practices, stakeholders can better understand and address the challenges posed by methane emissions to the environment and human health.

4.3.5. Limitations and Future Directions

Acknowledging the limitations of this paper is essential for a comprehensive understanding of its implications and for guiding future research endeavours:

4.3.6. Simplifications in Atmospheric Modeling

One limitation of the study is the simplifications made in modeling complex atmospheric processes that influence methane dispersion. Atmospheric dispersion models often rely on simplifying assumptions and parameterizations that may not fully capture the intricacies of atmospheric dynamics. Future research could explore more sophisticated modeling approaches to better represent the interactions between air velocity, temperature, and other meteorological variables in methane dispersion.

4.3.7. Uncertainties in Parameter Estimations

Another limitation is the uncertainties associated with parameter estimations used in the analysis. Parameters such as emission rates, atmospheric stability conditions, and surface characteristics can introduce uncertainties into the modeling process. Conducting sensitivity analyses and uncertainty quantification studies can help identify and quantify these uncertainties, thereby improving the reliability of model predictions.

4.3.8. Future Research Avenues

To address these limitations, future research could focus on exploring the interactive effects of air velocity, temperature, and other meteorological variables on methane dispersion in greater detail. Field experiments conducted under diverse environmental conditions can provide valuable data for validating model predictions and improving our understanding of methane dispersion processes in real-world settings. Additionally, advancements in observational techniques, such as remote sensing and atmospheric monitoring networks, can enhance our ability to collect high-resolution meteorological data for model validation and refinement, as recommended. In summary, the key findings of the discussion underscore the importance of considering air velocity, wind direction and ambient air temperature in understanding methane concentration dynamics and informing environmental policies and practices aimed at mitigating methane emissions and addressing climate change. Future research efforts should focus on exploring the interactive effects of meteorological variables on methane dispersion and conducting field experiments to validate model predictions under diverse environmental conditions.

5. Discussion and Findings

These bioenergy technologies and processes can indeed play a role in mitigating methane venting, particularly in the context of waste management and renewable energy production. As a matter of strategy to mitigate methane venting, the following processes are recommended as part of government policies to address the root cause of methane emissions.

Anaerobic Digestion: Anaerobic digestion is a biological process that breaks down organic materials, such as agricultural waste, food waste, and sewage sludge, in the absence of oxygen [7]. This process produces biogas, which is primarily methane and carbon dioxide. By capturing and utilizing the methane produced during anaerobic digestion, it can be used as a renewable energy source for electricity generation, heating, or vehicle fuel, thereby reducing methane emissions that would otherwise be released into the atmosphere. Rivers State is blessed with those critical feedstocks and can serve as a springboard for the bioenergy revolution in the State.

Landfill Gas Capture: Landfills are a significant source of methane emissions due to the decomposition of organic waste under anaerobic conditions. Landfill gas capture systems collect methane emitted from landfills and can either flare it off or utilize it for energy generation through processes similar to anaerobic digestion. This not only reduces methane emissions but also generates renewable energy.

Biological Methane Oxidation: Some bioenergy technologies focus on utilizing microbial processes to oxidize methane directly from sources such as wastewater treatment plants, agricultural operations, or natural wetlands. By promoting the activity of methane-oxidizing bacteria, these technologies can help mitigate methane emissions by converting methane into less potent greenhouse gases like carbon dioxide.

Ruminant Methane Reduction: Livestock, particularly ruminant animals like cattle, produce methane as a byproduct of digestion. Various strategies, including dietary supplements, feed additives, and genetic selection, can help reduce methane emissions from livestock. Bioenergy technologies can be employed to utilize methane emitted from manure management systems or to develop alternative feeds that minimize methane production in ruminants [6].

Biomass Gasification: Biomass gasification is a thermochemical process that converts organic materials, such as agricultural residues, forestry waste, or energy crops, into a gas mixture known as syngas (synthetic gas), which primarily contains hydrogen, carbon monoxide, and methane [9]. The syngas can be utilized for electricity generation, heat production, or as a feedstock for producing biofuels, thereby displacing fossil fuels and reducing overall methane emissions. Implementing these bioenergy technologies and processes can contribute to mitigating methane venting by capturing and utilizing methane emissions from various sources, thereby reducing their impact on climate change and promoting sustainable energy production. The synergies between bioenergy production and methane mitigation efforts are significant and multifaceted. Here are several ways in which these two areas can complement each other:

Carbon Sequestration and Methane Reduction: Some bioenergy feedstocks, such as energy crops and certain types of perennial grasses, have the potential to sequester carbon dioxide from the atmosphere through photosynthesis. By promoting the growth of these biomass feedstocks, bioenergy production can indirectly mitigate methane emissions by reducing the overall greenhouse gas concentration in the atmosphere. Additionally, bioenergy systems can help restore degraded lands, which may otherwise release methane due to anaerobic decomposition. Hence, tree planting should be encouraged around the State.

Co-Digestion and Co-Generation: Co-digestion involves combining multiple organic feedstocks with varying compositions in anaerobic digestion systems to enhance biogas production. By blending high-methane substrates with lower-quality feedstocks, such as crop residues or wastewater sludge, bioenergy production can optimize methane yield while efficiently treating organic waste streams. Co-generation systems that produce both heat and electricity from biogas or syngas can further enhance the efficiency and economic viability of bioenergy projects while mitigating methane emissions.

Livestock Waste Management: Livestock operations are a significant source of methane emissions due to enteric fermentation and manure management. Bioenergy technologies offer opportunities to capture methane emissions from manure and utilize them for energy production, thereby reducing methane venting while providing additional revenue streams for farmers. Moreover, implementing methane reduction strategies in livestock management, such as dietary interventions or improved manure management practices, can enhance the sustainability of bioenergy production systems. Overall, the integration of bioenergy production and methane mitigation efforts can result in mutually beneficial outcomes, including reduced greenhouse gas emissions, enhanced energy security, improved waste management, and sustainable rural development. These synergies underscore the potential for integrated approaches to address both environmental and energy challenges simultaneously in Rivers State.

Future research directions and opportunities for further advancements in methane mitigation within the context of chemical engineering and bioenergy encompass a wide range of interdisciplinary approaches. Here are some key areas where research efforts can focus to address challenges and leverage opportunities for innovation:

Catalytic Methane Conversion: Develop novel catalyst materials and reaction mechanisms for selective and efficient conversion of methane into value-added products, such as hydrogen, methanol, ethylene, and other chemicals. Explore advanced reactor designs and process intensification techniques to enhance the performance, stability, and scalability of methane conversion processes. Investigate integrated catalytic systems that utilize renewable energy sources or waste heat for methane activation and conversion, improving overall energy efficiency and sustainability. These can be achieved by supporting tertiary institutions in the state through research grants.

Microbial Electrolysis Cells (MECs): MECs utilize microbial communities to convert methane into hydrogen gas through electrochemical reactions, offering a potential pathway for methane valorization and energy storage.

Biological Methane Oxidation and Bioenergy: Explore microbial communities and metabolic pathways involved in methane oxidation processes to enhance our understanding of biological methane mitigation mechanisms. Develop engineered microbial systems or bioreactors with optimized performance for methane oxidation and bioenergy production applications. Investigate the potential synergies between biological methane oxidation and bioenergy production, such as co-cultivation strategies or integrated biorefinery concepts.

Carbon Capture and Utilization (CCU): Advance research on carbon capture technologies tailored specifically for methane-rich streams, such as biogas from anaerobic digestion or natural gas processing. Explore innovative CCU pathways for converting captured methane into valuable products, including chemicals, fuels, materials, and agricultural amendments. Investigate techno-economic and life-cycle assessments of CCU processes to evaluate their environmental and economic viability compared to conventional mitigation approaches.

Process Integration and Optimization: Develop integrated systems and optimization strategies that combine methane mitigation technologies with bioenergy production, waste management, and renewable energy generation. Explore synergies between different methane mitigation approaches, such as combining biological, chemical, and physical methods for enhanced performance and cost-effectiveness. Apply advanced process modeling, simulation, and control techniques to optimize the design and operation of methane mitigation processes in diverse applications and scales.

Sustainable Methane Supply Chains: Investigate strategies for sustainable sourcing of methane feedstocks, including biogas, natural gas, and methane-rich waste streams, to ensure long-term availability and environmental integrity. Explore circular economy approaches that integrate methane mitigation technologies with other sectors, such as agriculture, wastewater treatment, and industrial manufacturing, to maximize resource utilization and minimize environmental impacts. Assess the environmental, social, and economic implications of methane mitigation technologies across the entire supply chain, from feedstock production to end-use applications, to inform decision-making and policy development. Emerging technologies and innovations for methane capture and utilization are continuously evolving to improve efficiency, reduce costs, and enhance environmental performance. Here are some advancements in methane capture, monitoring, and conversion processes, including innovations in sensor technology and remote monitoring.

5.1. Advanced Anaerobic Digestion Systems

High-Solids Anaerobic Digestion: This technology allows for the digestion of solid organic waste materials with minimal water content, improving process efficiency and reducing energy requirements.

Thermophilic Digestion: Operating anaerobic digestion at higher temperatures (thermophilic conditions) can enhance methane production rates and pathogen destruction while reducing retention times.

Hybrid Digestion Systems: Integrating different digestion processes, such as anaerobic digestion with aerobic treatment or gasification, can improve overall waste treatment efficiency and biogas yield.

5.2. Enhanced Methane Detection and Monitoring

Next-Generation Gas Sensors: Advanced gas sensors with improved sensitivity, selectivity, and durability enable real-time monitoring of methane emissions at various sources, including landfills, oil and gas facilities, and agricultural operations.

Drone-Based Monitoring: Unmanned aerial vehicles (drones) equipped with methane sensors and imaging systems offer cost-effective and rapid detection of methane leaks over large areas, such as pipelines, well pads, and infrastructure (Figure 10).

Figure 10: Drone-Based Monitoring

5.3. Remote Monitoring and Control Systems

IoT-enabled Monitoring Platforms: Internet-of-Things (IoT) technologies enable remote monitoring and control of methane capture and utilization systems, allowing operators to optimize performance, detect anomalies, and respond to operational issues in real-time [10] (Figure 11).

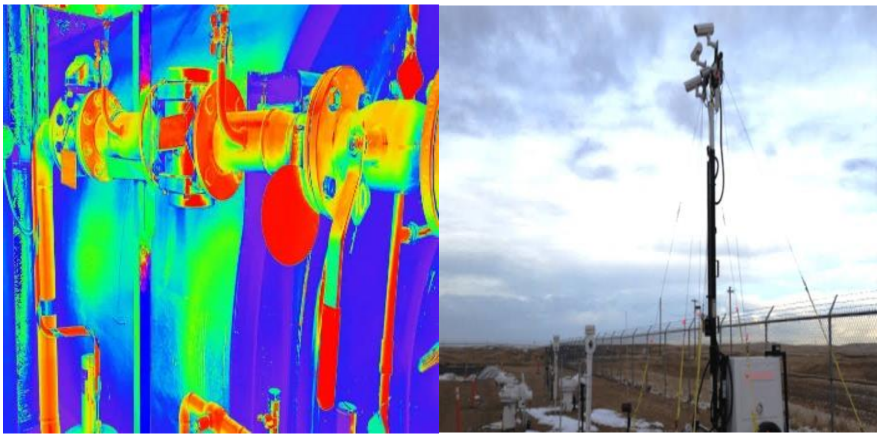

Figure 11: Infrared camera installation along the pipeline for real-time monitoring

Cloud-Based Data Analytics: Cloud computing and data analytics platforms facilitate the analysis of large datasets generated by methane monitoring systems, providing insights into emission patterns, trends, and optimization opportunities. Overall, future research in methane mitigation within the context of chemical engineering and bioenergy should embrace interdisciplinary collaboration, innovation, and systems thinking to address complex environmental challenges and accelerate the transition toward a sustainable and low-carbon future. Analyzing the economic feasibility of methane mitigation strategies involves conducting comprehensive cost-benefit analyses to assess the financial viability and potential revenue streams associated with methane capture and utilization initiatives. Here's an overview of the key factors to consider in evaluating the economic feasibility of methane mitigation strategies:

5.4. Cost of Methane Mitigation Technologies

Initial Capital Costs: This includes the investment required for equipment, infrastructure, and installation of methane capture and utilization systems, such as anaerobic digesters, biogas upgrading units, or catalytic converters.

Operating and Maintenance Costs: These ongoing expenses encompass labour, energy, materials, and maintenance activities associated with operating methane mitigation technologies, including monitoring, cleaning, repairs, and replacement of components.

5.5. Benefits of Methane Emission Reduction

Greenhouse Gas Emission Reductions: Quantifying the avoided emissions of methane, a potent greenhouse gas, and estimating the associated social and environmental benefits, such as mitigating climate change impacts, improving air quality, and reducing public health risks.

Compliance and Regulatory Benefits: Assessing the value of compliance with local, regional, or national regulations, emission reduction targets, or carbon pricing mechanisms that incentivize methane mitigation efforts.

5.6. Revenue Streams from Methane Capture and Utilization

Sale of Renewable Energy: Generating revenue from the sale of renewable energy products derived from captured methane, such as biogas, renewable natural gas (RNG), electricity, or heat, to utilities, industries, or end-users.

Carbon Credits and Offsets: Participating in carbon markets or offset programs to monetize emission reductions achieved through methane mitigation projects, potentially generating additional revenue streams.

Value-Added Products: Producing and selling value-added products derived from methane conversion processes, such as chemicals, fuels, biomaterials, or agricultural amendments, to commercial markets.

5.7. Economic and Financial Metrics

Return on Investment (ROI): Calculating the financial return on capital investment in methane mitigation technologies by comparing the net present value of project revenues and savings to the initial investment costs.

Payback Period: Determining the time required for methane mitigation projects to recoup their initial investment through revenue generation and cost savings.

Internal Rate of Return (IRR): Evaluating the project's profitability by estimating the annualized percentage rate of return on invested capital over the project's life cycle.

Net Present Value (NPV): Assessing the project's economic value by calculating the present value of expected future cash flows, considering factors such as discount rates, inflation, and project risks.

5.8. Risk and Uncertainty Analysis

Conducting sensitivity analysis to evaluate the impact of key variables, such as energy prices, feedstock costs, regulatory changes, or technological advancements, on the economic performance of methane mitigation projects. Assessing project risks, including technical, financial, market, regulatory, and operational risks, and implementing risk management strategies to mitigate potential adverse impacts on project economics. By integrating these analyses, stakeholders can make informed decisions regarding the economic feasibility of methane mitigation strategies, identify opportunities for revenue generation, and optimize the allocation of resources to maximize the financial and environmental benefits of methane capture and utilization initiatives.

6. Conclusion

The net methane emissions (mg/l) for Soku, Agbada, and Oyigbo were 0.90, 0.28, and 1.03 respectively. The corresponding temperature rise for the host communities over the same period were 1.87 oC, 0.37 oC, and 1.16 oC, respectively. Using Monin-Obukhov length for methane dispersion, the dispersion was near neutral unstable for all three facilities. The Monin-Obukhov lengths for facilities A, B, and C were, respectively, meaning methane dispersion in those facilities is near neutral unstable, meaning more parameters like wind direction should be factored into the analysis for efficient description of methane dispersion in the three facilities. Furthermore, the paper evaluates the environmental and socio-economic implications of implementing methane mitigation strategies, considering factors such as energy efficiency, carbon footprint reduction, and air quality improvement in Rivers State. Ultimately, this paper contributes to the discourse on methane emissions reduction by providing insights into effective strategies and their implications for both bioenergy development and environmental stewardship. By fostering interdisciplinary collaboration and innovation, it seeks to accelerate progress towards a more sustainable and resilient future.

Acknowledgment: We extend our sincere appreciation to Prof. Ipeghan Otaraku for his exceptional support and inspiration throughout this research work and beyond. The conducive learning environment and resources provided in the course modules by the University of Port Harcourt played a pivotal role in the successful completion of this research work. We also wish to express our appreciation to our families for their unwavering support during the challenging phases of this research journey, special thanks to Engr. Proper Otokpa.

Data Availability Statement: The datasets utilized and analyzed during this study are openly available on ResearchGate and Journal for Newviews in Engineering. We embrace the principles of transparency and open science, inviting fellow researchers to access, utilize, and build upon these datasets for further exploration.

Funding Statement: This research was self-funded, as all authors independently pursued this project out of personal interest following the completion of a module in our course of study facilitated by Prof. Ipeghan Otaraku at the University of Port Harcourt, Nigeria.

Conflicts of Interest Statement: All authors declare that there are no conflicts of interest regarding the publication of this paper. This project was conducted with integrity, ensuring independence from any external influences that could compromise the objectivity of the study or the reporting of its findings. Furthermore, all references from which the data were obtained are duly acknowledged within this publication.

Ethics and Consent Statement: This study adhered to the ethical standards and guidelines. All research protocols were thoroughly reviewed and approved by the lead supervisor, Prof. Ipeghan Otaraku.

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