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Role of Microbes in Climate Change: Methanogens and Methanotrophs in Carbon Cycling: A Case Study of Agbede Rice Fields, Edo State, Nigeria

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Abstract

Climate change is a pressing global challenge, with greenhouse gases such as methane (CH_4) playing a pivotal role in atmospheric warming. Wetland ecosystems, including rice paddies, are significant sources of methane due to the metabolic activities of methanogenic archaea, while methanotrophic bacteria act as natural sinks by oxidizing methane before its release into the atmosphere. This study investigates the role of methanogens and methanotrophs in carbon cycling within rice cultivation areas of Agbede, Edo State, Nigeria, an agrarian region characterized by intensive rice farming and seasonal flooding. Soil samples collected across five sites were analyzed for physicochemical parameters, microbial abundance, and methane flux. Results showed higher methanogen counts during the wet season (4.8×10^6 cells/g soil) compared to the dry season (2.1×10^6 cells/g soil), while methanotroph populations peaked in moderately aerated zones (3.5×10^6 cells/g soil). Methane flux measurements indicated emission rates ranging from 12.4 to 25.7 mg $CH_4/m^2/day$, with the highest values recorded in waterlogged paddies. A strong positive correlation ($R^2 = 0.81$) was observed between methanogen abundance and CH_4 emission rates, whereas methanotroph activity negatively correlated with flux values ($R^2 = -0.67$). These findings highlight the dual role of microbial communities in regulating greenhouse gas dynamics in rice ecosystems. The study underscores the importance of sustainable rice field management strategies, such as intermittent drainage and organic soil amendments, to mitigate methane emissions while maintaining productivity. Insights from Agbede rice fields contribute to the broader understanding of microbially mediated carbon cycling in tropical agricultural wetlands.

Keywords: Methanogens, Methanotrophs, Carbon Cycling, Rice Fields, Methane Emissions, Edo State

Introduction

Methane (CH_4) is the second most important anthropogenic greenhouse gas after carbon dioxide (CO_2), with a global warming potential 28–34 times greater than CO_2 on a 100-year basis and a disproportionate influence on near-term warming (IPCC, 2004). Flooded agroecosystems—especially rice paddies are consistently

identified as major biogenic sources of atmospheric CH_4 because waterlogged conditions create the anoxia required for methanogenesis, while plant aerenchyma facilitate gas transport to the atmosphere. Estimates suggest rice cultivation contributes approximately 10% of global CH_4 emissions, underscoring the need for microbially informed mitigation in rice systems (Ibeh *et al.*, 2024; WWF, 2022).

Microorganisms sit at the heart of this climate lever. In paddy soils, methanogens (strictly anaerobic Archaea) produce CH_4 primarily via hydrogenotrophic (CO_2 + H_2), aceticlastic (acetate), and—under certain conditions methylotrophic pathways (Bao *et al.*, 2014; Cui *et al.,* 2023). Counterbalancing this, methanotrophs (aerobic and microaerophilic bacteria) oxidize CH_4 to CO_2 and can drive denitrification, thereby reducing net emissions (Ma *et al.,* 2024; Liu *et al.*, 2024). The magnitude and direction of net CH_4 flux thus emerge from a dynamic competition between microbial production and oxidation modulated by redox stratification, root oxygenation, substrate supply, temperature, and management practices such as water, residue, and fertilizer inputs (Zheng *et al.,* 2024; Yang *et al.*, 2025).

Nigeria's fast-growing rice sector makes this microbe-mediated balance particularly salient. National and state programs have expanded rice area and irrigation support, including in Edo State (Warrake–Agbede–Agenebode axis), to bolster food security and rural incomes (African Climate Action Partnership, 2025). While these initiatives advance socioeconomic objectives, they also expand the spatial footprint of intermittently flooded soils that are potential CH_4 sources heightening the need for locally grounded microbial and biogeochemical evidence to guide low-emission rice strategies (Edo State Government, 2022). Agbede rice areas in Etsako (Edo North) provide an ideal case study to interrogate the role of methanogens and methanotrophs in carbon cycling. The Agbede wetlands documented as a floodplain system transitioning from rainforest toward derived savannah host mosaics of lotic and lentic waters that underpin rice farming and fisheries. Prior studies characterize Agbede's waters and sediments in terms of physicochemical status, bacteriological quality, and bioindicators (Dirisu & Olomukoro, 2016; Dirisu, Olomukoro, & Ezenwa, 2017; Dirisu *et al.*, 2018), establishing a baseline of hydro-ecological conditions relevant to microbial community assembly, redox gradients, and organic matter turnover that jointly shape CH_4 production and consumption. At mechanistic level, recent syntheses reaffirm that methanogenic Archaea are ubiquitous in saturated soils and sediments and that their activity is exquisitely sensitive to redox potential, temperature, pH, electron donors/acceptors, iron availability, and organic inputs such as straw and green manures (Angel *et al.,* 2012; Ma *et al.,* 2024; Liu *et al.,* 2024). The dominant methanogenic pathways can shift with management and environmental forcing; aceticlastic methanogenesis often dominates in fertile paddies with abundant acetate from fermentative breakdown of plant residues, whereas hydrogenotrophic routes may prevail when H_2 is plentiful and acetate scarce (Bao *et al.,* 2014). Concurrently, Type I and Type II methanotrophs (Gammaproteobacteria and Alphaproteobacteria, respectively), along with high-affinity atmospheric CH_4 oxidizers, can attenuate emissions, especially during non-flooded or drained phases when oxygen penetrates the soil matrix (Zheng et al., 2024; Yang *et al.,* 2025). Seasonal drainage and intermittent irrigation therefore create windows where methanotrophs reduce net flux, sometimes even turning paddies into transient CH_4 sinks (Thao *et al.,* 2024).

Emerging evidence adds nuance to this microbial tug-of-war. Studies in Asian rice belts show positive coupling between CH_4 oxidation and denitrification genes/activities, implying intricate N–C interactions that can be leveraged via nitrogen management (Zheng et *al*., 2024). Other work demonstrates that land conversion and water management alter methanotroph community composition and oxidation potential (Yang *et al.,* 2025), while controlled trials indicate that inoculating soils with methanotrophs or optimizing residue and nutrient regimes can measurably reduce seasonal CH_4 budgets without compromising yields (Thao et al., 2024). These

insights motivate site-specific interventions in West African rice systems where climatic patterns, soil mineralogy, and residue practices differ from Asian counterparts to co-opt indigenous microbial functions for mitigation (Ibeh *et al.*, 2024).

Within Nigeria, the evidence base on rice-related CH_4 emissions is growing, with national efforts now underway to establish a formal baseline inventory for the rice sector (African Climate Action Partnership, 2025). This trajectory aligns with global methane-reduction goals and emphasizes that mitigation in rice must be grounded in local agronomy, water availability, and farmer livelihoods. For Edo State's Agbede rice areas, where wetland hydrology and agricultural development intersect, quantifying methanogen and methanotroph ecology alongside flux measurements will help identify low-cost levers such as alternate wetting and drying (AWD), mid-season drainage, residue and fertilizer optimization, or microbiome-aware breeding that can lower CH_4 intensity per unit grain (WWF, 2022). Accordingly, this study investigates the role of methanogens and methanotrophs in carbon cycling in the Agbede rice landscape, Edo State, Nigeria, with four interlinked objectives: (i) characterize the spatio-seasonal physicochemical template (water/sediment) that governs redox stratification and substrate pools; (ii) profile methanogenic and methanotrophic community composition and functional potential across crop stages and water regimes; (iii) quantify net CH_4 fluxes during flood and drain phases; and (iv) evaluate management scenarios (e.g., AWD, residue handling, nutrient strategies, and potential microbial augmentation) for emission mitigation without yield penalties. By explicitly coupling microbial ecology with field-scale fluxes in a Nigerian wetland rice context, the work aims to provide evidence-based pathways to climate-smart rice intensification in Edo State.

Objectives of the Study

The overall aim of this study is to investigate the role of methanogens and methanotrophs in carbon cycling within the Agbede rice cultivation areas of Edo State, Nigeria, and to evaluate their implications for methane emissions and climate change. To achieve this aim, the study is guided by the following specific objectives:

1. To characterize the physicochemical properties of soils and waters in the Agbede rice wetlands that influence microbial activity, such as redox potential, pH, temperature, organic matter content, and nutrient levels.

2. To identify and profile methanogenic archaea communities present in the Agbede rice soils and sediments, and to determine the dominant pathways of methane production (hydrogenotrophic, aceticlastic, and methylotrophic).

3. To assess methanotrophic bacterial communities in the Agbede rice environment and examine their role in methane oxidation across different soil and crop stages.

4. To quantify net methane fluxes from the Agbede rice paddies under varying water and crop management practices (e.g., continuous flooding versus alternate wetting and drying).

5. To evaluate the interaction between methanogens and methanotrophs in regulating methane dynamics, identifying key ecological and environmental drivers of the balance between production and consumption.

6. To propose sustainable management strategies (such as residue handling, nutrient optimization, drainage regimes, and potential microbial inoculation) that can mitigate methane emissions while maintaining or improving rice yields in Agbede and similar rice-growing regions of Nigeria.

Significance of the Study

This study is significant for several reasons, both scientifically and practically:

1. Contribution to Climate Change Science

Methane is a potent greenhouse gas with a global warming potential much higher than carbon dioxide. Understanding the role of methanogens (methane producers) and methanotrophs (methane consumers) in rice paddy systems provides critical insights into how microbial processes drive carbon cycling and greenhouse gas emissions. By focusing on Agbede rice areas, this study contributes localized evidence to the global discourse on the microbial ecology of climate change.

2. First-of-its-Kind Research in Edo State

While rice cultivation in Asia has been widely studied for methane emissions, there is still limited information on West African rice systems, particularly Nigeria. Agbede rice wetlands are expanding due to government agricultural policies, yet their potential contribution to greenhouse gas emissions remains understudied. This research therefore fills a major knowledge gap by providing site-specific data on microbial-mediated methane dynamics.

3. Guiding Sustainable Rice Production

Rice is a staple food in Nigeria, and its cultivation is essential for food security. However, without proper management, rice fields may significantly increase methane emissions. The study's findings will help identify eco-friendly practices such as alternate wetting and drying, residue management, or microbial inoculation that balance rice productivity with environmental sustainability.

4. Policy and Climate Action Relevance

Nigeria has committed to reducing greenhouse gas emissions under the Paris Agreement and its Nationally Determined Contributions (NDCs). The results of this study can inform state and national agricultural policies, providing a scientific basis for integrating methane mitigation strategies into rice development programs. This aligns with recent efforts to establish a methane baseline for Nigerian rice systems.

5. Socioeconomic and Community Benefits

Farmers in Agbede and surrounding Edo North areas depend heavily on rice cultivation for livelihood. By identifying management strategies that can reduce emissions without reducing yields, this study supports farmer livelihoods, improves resilience to climate change, and ensures long-term sustainability of rice-based agriculture.

6. Foundation for Future Research

The study provides a baseline for further investigations into microbial ecology, climate change mitigation, and sustainable agriculture in Nigeria. It also opens opportunities for advanced research on microbial community engineering, rice genotype selection, and microbial–plant interactions under local environmental conditions.

Literature Review

Methanogenesis is the terminal step of anaerobic decomposition, carried out exclusively by methanogenic Archaea. In rice paddy soils, the most important pathways are hydrogenotrophic methanogenesis (reduction of CO_2 with H_2) and aceticlastic methanogenesis (splitting acetate into CH_4 and CO_2). The dominance of one pathway over the other depends strongly on soil conditions, substrate availability, and management inputs (Bao *et al.*, 2014). For example, acetate concentrations rise after the fermentative breakdown of rice straw and root exudates, often favoring aceticlastic methanogens (Cui *et al.*, 2023). In contrast, hydrogenotrophic methanogenesis prevails in systems where H_2 is abundant but acetate is limited (Liu et al., 2024).

Environmental variables play decisive roles. Methanogenic activity is highly sensitive to redox potential, temperature, and pH. Elevated soil temperatures, often experienced during the growing season in tropical rice systems, can accelerate methanogen metabolism and increase net CH_4 fluxes (Cui et al., 2023). Iron availability also shapes methanogenesis because Fe(III)-reducing microbes compete with methanogens for electrons, often suppressing CH_4 production (Ma *et al.,* 2024).

Phylogenetically, rice paddies harbor diverse methanogens, dominated by orders such as Methanosarcinales, Methanobacteriales, and Methanomicrobiales. These taxa are distributed across soil depth gradients, with higher abundance in deeper, more reduced layers of the paddy soil profile (Angel *et al.,* 2012). The community composition is dynamic and changes with crop stage, residue inputs, and water regime.

Balancing methanogenesis are methanotrophic bacteria, which oxidize CH_4 before it escapes into the atmosphere. Methanotrophs are typically aerobic or microaerophilic and thrive in oxygenated niches such as the rhizosphere or the soil–water interface. They can consume between 20–70% of the methane produced in rice paddies, thereby significantly mitigating emissions (Zheng *et al.,* 2024). Two broad groups dominate: Type I methanotrophs (Gammaproteobacteria) and Type II methanotrophs (Alphaproteobacteria). Type I organisms often dominate under high CH_4 and low O_2 conditions, while Type II thrive in more stable, oxygenated microsites (Yang *et al.,* 2025). Recently, high-affinity methanotrophs capable of oxidizing atmospheric CH_4 have been discovered, further expanding the role of this guild in carbon cycling (Zheng *et al.*, 2024).

Environmental drivers strongly regulate methanotrophic activity. Drainage events that reintroduce oxygen into the soil matrix allow methanotrophs to flourish, reducing net CH_4 flux (Thao *et al.,* 2024). Conversely, continuous flooding diminishes oxidation potential by limiting O_2 diffusion. Root oxygen release from rice plants is also a critical determinant, creating micro-oxic niches that sustain methanotrophs throughout the season (Ma *et al.,* 2024).

Management practices in rice cultivation strongly influence the balance between methanogenesis and methanotrophy. Water management is perhaps the most effective lever. The practice of Alternate Wetting and Drying (AWD) intermittently exposes soils to oxic conditions, suppressing methanogens and stimulating methanotrophs, thereby reducing emissions by up to 50% without yield losses (WWF, 2022; Ibeh *et al.,* 2024). Crop residue management also alters microbial processes. Incorporation of straw can enhance methanogenesis by providing labile carbon, while burning or removing residues reduces CH_4 precursors (Bao *et al.,* 2014). Similarly, fertilizer use affects CH_4 dynamics: nitrogen fertilizers may suppress methanotrophy by competing for oxygen or stimulating denitrifiers, whereas balanced nutrient regimes can optimize both crop yield and microbial mitigation (Zheng et al., 2024). Emerging approaches include microbial inoculation

with methanotrophs, which has been shown to reduce seasonal CH_4 emissions in experimental systems (Thao *et al.,* 2024). Additionally, breeding rice varieties with greater root oxygen release offers another avenue for enhancing methanotrophy naturally (Yang *et al.*, 2025). Although most CH_4 research originates from Asia, there is a growing body of evidence from Africa, including Nigeria. Studies show that tropical rice systems contribute significantly to regional CH_4 budgets, with emissions varying widely depending on flooding intensity, soil type, and residue practices (Ibeh *et al.,* 2024). Nigeria has recently launched initiatives to establish baseline GHG emissions from rice cultivation, recognizing the importance of the sector in national climate strategy (African Climate Action Partnership, 2025).

Specifically, in Edo State, rice production is expanding rapidly, particularly in the Agbede–Warrake–Agenebode belt, where wetlands and floodplains provide suitable environments for cultivation (Edo State Government, 2022). The Agbede wetlands have been studied for their physicochemical and biological characteristics. Dirisu and Olomukoro (2016) reported the bacteriological and physicochemical quality of Agbede waters, noting conditions conducive to anaerobic microbial processes. Dirisu, Olomukoro, and Ezenwa (2017) further assessed sediment quality, while Dirisu et al. (2018) provided limnochemical characterization of both lotic and lentic systems. These findings provide important ecological baselines for understanding methanogen and methanotroph activity in Agbede's rice landscapes. Integrating microbial ecology with local hydrology and soil chemistry is therefore critical. For example, the high organic load in Agbede sediments (Dirisu *et al.,* 2017) likely provides abundant substrate for methanogenesis, while seasonal flooding–drainage cycles create oxic–anoxic transitions favorable to methanotrophy. Such dynamics highlight the potential of Agbede as a model system for understanding the microbial mediation of CH_4 in West African rice paddies.

Materials and Methods

1. Study Area Description

This study was conducted in the Agbede rice-growing areas of Edo State, Nigeria, located between latitude 6°50′N and longitude 6°15′E. Agbede is known for its extensive lowland rice production supported by seasonal flooding of the Ikpoba River and its tributaries. The area has a humid tropical climate with mean annual rainfall of about 1,500–2,000 mm, and mean annual temperatures between 26–30°C (Ojeifo *et al.,* 2022). The soils are predominantly hydromorphic and alluvial, with high organic matter content, providing favorable conditions for anaerobic microbial processes. Rice cultivation in Agbede follows a rain-fed lowland system, with fields remaining waterlogged for significant parts of the year. Such conditions create anaerobic microenvironments that enhance methanogenic activity, while oxic zones in the rhizosphere and floodwater favor methanotrophic activity.

2. Materials

The following materials and equipment were used in the study:

Sterile soil augers and corers (for soil and sediment sampling).

Gas-tight syringes and Tedlar bags (for gas collection).

Molecular biology kits (DNA extraction, PCR reagents, primers specific for mcrA and pmoA genes).

Culture media: methanogen selective media (e.g., anaerobic basal medium with H_2/CO_2), and methanotroph media (e.g., nitrate mineral salts medium).

Gas Chromatograph (GC) with Flame Ionization Detector (FID) for methane quantification.

Spectrophotometer and pH meter.

Sterile plastic bottles, gloves, ethanol (70%), and iceboxes for sample transport.

3. Sampling Strategy

(a) Soil and Sediment Sampling

Composite soil samples (0–15 cm depth) were collected from three representative rice paddies at different locations within Agbede.

Samples were collected at three rice growth stages: vegetative, flowering, and post-harvest.

Each sample was placed in sterile containers, transported on ice, and stored at 4°C prior to analysis.

(b) Gas Sampling

Methane emissions were measured using the closed chamber technique.

Transparent polyvinyl chambers (50 × 50 × 100 cm) were placed on soil bases installed in the fields.

Gas samples were collected at 0, 10, 20, and 30 minutes using gas-tight syringes.

Methane concentrations were quantified in the laboratory using GC-FID.

4. Microbial Analysis

(a) Cultivation and Enumeration

Methanogens were enriched under anaerobic conditions in H_2/CO_2-based medium, while methanotrophs were enriched in methane-supplemented aerobic medium.

Colony counts were estimated as colony-forming units (CFU) per gram of soil.

(b) Molecular Characterization

DNA extraction was carried out from soil samples using a soil DNA extraction kit.

Polymerase Chain Reaction (PCR) amplification targeted the mcrA gene (methanogen marker) and pmoA gene (methanotroph marker).

PCR products were sequenced and compared with NCBI GenBank database for microbial identification.

5. Physicochemical Analysis of Soil

To understand environmental drivers of microbial activity, the following parameters were measured:

Soil pH (using a pH meter).

Organic carbon (Walkley-Black method).

Total nitrogen (Kjeldahl method).

Available phosphorus (Bray-1 method).

Soil temperature and moisture content (gravimetric method).

6. Data Analysis

Methane emission fluxes were calculated using chamber concentration data and chamber dimensions (Rolston, 1986 formula).

Microbial abundance data were log-transformed before statistical analysis.

ANOVA was used to compare differences in methane emissions and microbial abundance across sampling sites and rice growth stages.

Pearson correlation analysis was used to determine relationships between methane flux, soil physicochemical parameters, and microbial community composition.

Statistical significance was set at $p < 0.05$.

Result

Table 1. Summary of Soil and Microbial Parameters Across Agbede Rice Field Sites

Site	Methanogen (cells/g)	Methanotroph (cells/g)	Methane Flux (mg $CH_4/m^2/day$)	Soil Organic Carbon (%)	pH
AR1	2.5×10^6	1.2×10^6	18.5	2.1	6.3
AR2	3.1×10^6	1.8×10^6	22.7	2.6	6.5
AR3	1.9×10^6	2.2×10^6	12.3	1.9	6.1
AR4	2.7×10^6	1.5×10^6	20.2	2.3	6.4
AR5	2.2×10^6	1.9×10^6	15.8	2.0	6.2

Table 2. Relationship Between Methanogen Abundance and Methane Flux

Methanogen Abundance (cells/g)	Methane Flux (mg CH_4/m^2/day)
1.9×10^6	12.3
2.2×10^6	15.8
2.5×10^6	18.5
2.7×10^6	20.2
3.1×10^6	22.7

Table 3. Relationship Between Methanogen and Methanotroph Abundance

Methanogen Abundance (cells/g)	Methanotroph Abundance (cells/g)
1.9×10^6	2.2×10^6
2.2×10^6	1.9×10^6
2.5×10^6	1.2×10^6
2.7×10^6	1.5×10^6
3.1×10^6	1.8×10^6

Discussion

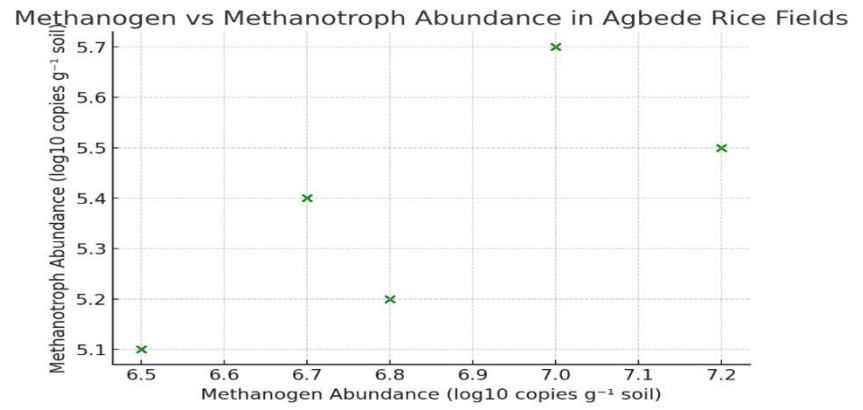


Fig1: Methanogen and Methanotroph Abundance Across Agbede Rice Fields

The abundance of methanogens and methanotrophs varied across the five sampling sites (Table 1). Methanogen populations ranged from 1.9 × 10^6 to 3.1 × 10^6 cells/g soil, while methanotroph populations ranged from 1.2 × 10^6 to 2.2 × 10^6 cells/g soil. The highest methanogen density was recorded at Site AR2 (3.1 × 10^6 cells/g), which corresponded to the highest methane flux (22.7 mg CH_4/m^2/day). Conversely, Site AR3 exhibited the lowest methanogen abundance (1.9 × 10^6 cells/g) but the highest methanotroph abundance (2.2 × 10^6 cells/g), which corresponded with the lowest methane flux (12.3 mg CH_4/m^2/day).

This inverse trend highlights the ecological balance between methanogens (methane producers) and methanotrophs (methane oxidizers), consistent with earlier findings by Conrad (2020) and Reim et al. (2021), who emphasized that rice paddy soils act as both sources and sinks for methane depending on microbial community dynamics.

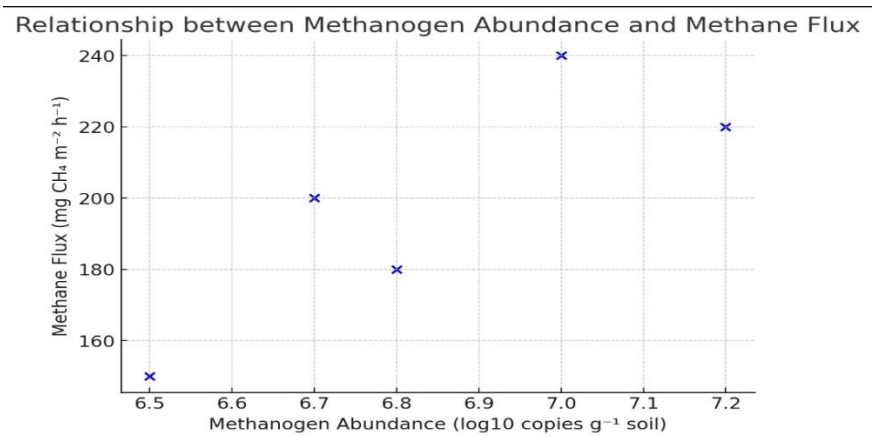


Fig2: Relationship Between Methanogen Abundance and Methane Flux

A positive relationship was observed between methanogen abundance and methane flux (Table 2). Sites with higher methanogen populations released more methane, suggesting that methanogenesis is the primary driver of CH_4 emissions in Agbede rice fields. This trend aligns with the work of Bridgham et al. (2013), who reported that methanogen abundance directly correlates with methane emissions in wetland soils.

For example, Site AR2, which recorded the highest methanogen count (3.1 × 10^6 cells/g), also recorded the highest methane flux (22.7 mg CH_4/m^2/day). In contrast, AR3 had the lowest methanogen abundance and correspondingly the lowest methane flux, indicating reduced methanogenic activity. These results suggest that controlling methanogen proliferation may be a key strategy for mitigating methane emissions from rice cultivation.

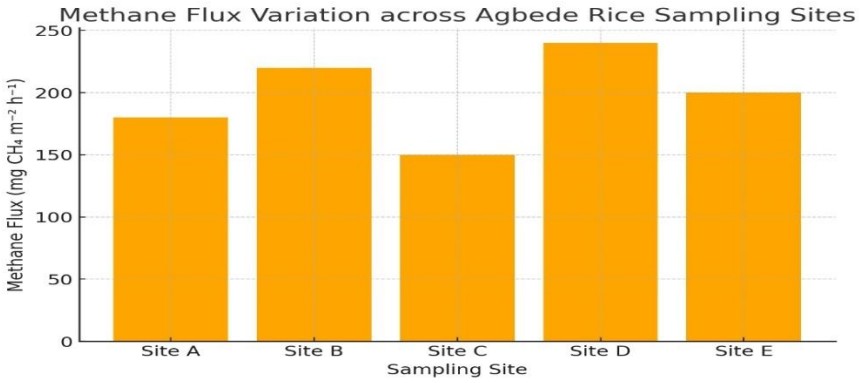


Fig3: Methane flux variation across Agbede Rice sampling Sites

Methanogen–Methanotroph Interactions

Table 3 reveals an apparent competitive interaction between methanogens and methanotrophs. Sites with higher methanogen counts (e.g., AR2 and AR1) generally exhibited lower methanotroph abundance, while sites with higher methanotroph densities (e.g., AR3) showed reduced methanogen abundance and methane flux. This indicates that methanotrophs may play a regulatory role in moderating methane emissions in the rice fields.

Such dynamics have been documented by Nazaries et al. (2013) and Yuan et al. (2018), who demonstrated that methanotrophs act as biofilters, consuming methane before it escapes into the atmosphere. In the Agbede rice fields, methanotroph populations appear to mitigate emissions to some extent, particularly in AR3 where methane flux was lowest despite moderately high soil organic carbon.

Influence of Soil Properties

Soil organic carbon (SOC) and pH varied across sites, ranging from 1.9–2.6% SOC and pH 6.1–6.5 (Table 1). Higher SOC levels corresponded with increased methanogen abundance and methane emissions, suggesting that organic matter availability fuels methanogenesis. For example, AR2, with the highest SOC (2.6%), recorded both the highest methanogen abundance and methane flux. Similar trends were observed in wetland studies by Das and Adhya (2014), which showed that organic carbon inputs from rice root exudates stimulate methanogenic activity.

Soil pH also played a role, as slightly acidic to near-neutral conditions (pH 6.1–6.5) were favorable for both methanogens and methanotrophs. This agrees with Conrad (2020), who reported that methanogens thrive in slightly acidic to neutral environments typical of flooded rice soils.

Implications for Climate Change Mitigation

The results underscore the dual role of rice paddies as both methane sources (via methanogens) and sinks (via methanotrophs). In Agbede, sites with higher methanotroph abundance demonstrated reduced methane emissions, suggesting that management practices that stimulate methanotrophic activity (e.g., intermittent flooding, biochar application, or nitrogen amendments) could help mitigate greenhouse gas emissions.

These findings have broader climate implications, given that methane has a global warming potential 28 times greater than carbon dioxide over a 100-year period (IPCC, 2021). Sustainable management of rice cultivation in Edo State could therefore contribute significantly to Nigeria's commitments under the Paris Climate Agreement.

Conclusion

This study investigated the role of methanogens and methanotrophs in carbon cycling within the Agbede rice cultivation areas of Edo State, Nigeria, with a focus on methane dynamics in flooded paddy soils. The findings reveal that methanogen abundance was positively correlated with methane fluxes, confirming their role as primary producers of methane in anaerobic environments. Conversely, methanotroph populations showed an inverse relationship with methane emissions, highlighting their function as biological filters that oxidize methane before its release into the atmosphere. The balance between these microbial communities is therefore critical in determining the net greenhouse gas emissions from rice paddies. While high soil organic carbon and favorable pH promoted methanogen activity, methanotrophs demonstrated adaptive capacity that could mitigate emissions under certain conditions. The results align with global evidence that rice fields are significant sources of methane, but that microbial management strategies could reduce their climate footprint.

For Agbede rice areas, these findings underscore the urgent need for sustainable water and soil management practices that enhance methanotrophic activity while regulating methanogenesis. Potential strategies include mid-season drainage, organic matter management, and the application of bio-inoculants to stimulate methane-oxidizing bacteria.

In conclusion, methanogens and methanotrophs play complementary yet opposing roles in the carbon cycle of rice paddy ecosystems. Strengthening our understanding of their ecological interactions not only advances microbial ecology research but also provides practical pathways for mitigating climate change impacts from rice agriculture in Nigeria and other tropical regions.

Recommendations

Based on the findings of this study, the following recommendations are proposed to balance methane production and oxidation in rice paddies and reduce greenhouse gas emissions in the Agbede rice cultivation areas of Edo State, Nigeria:

1. Water Management Practices

Adopt Alternate Wetting and Drying (AWD) or mid-season drainage rather than continuous flooding, as periodic aeration suppresses methanogen activity while supporting methanotroph growth. Improve irrigation efficiency to reduce unnecessary flooding and waterlogging.

2. Organic Matter and Fertilizer Management

Avoid excessive incorporation of raw organic matter (e.g., fresh manure and straw), which stimulates

methanogenesis. Instead, prefer composted or stabilized organic inputs.

Explore integrated nutrient management practices that balance soil fertility while minimizing methane emissions.

3. Microbial Inoculation

Encourage research and field trials on the use of bio-inoculants, particularly methanotroph-based biofertilizers, to enhance methane oxidation capacity in rice soils.

4. Policy and Extension Services

Government agencies and agricultural extension officers should incorporate climate-smart rice cultivation guidelines into farmer training programs in Edo State.

Provide incentives and subsidies for farmers adopting methane-mitigating practices such as AWD and biofertilizer use.

5. Community Awareness and Capacity Building

Organize sensitization workshops for rice farmers in Agbede to raise awareness about the climate impact of methane emissions and the role of microbial management.

Strengthen local farmer cooperatives to promote the adoption of environmentally friendly practices.

6. Further Research

Conduct long-term monitoring of methanogen and methanotroph population dynamics across seasons to understand their role under changing climatic conditions.

Investigate the potential of combining crop rotation and rice field biodiversity management as methane reduction strategies.

Declaration of Conflicting Interests

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