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COMPARATIVE ANALYSIS OF METHANE EMISSION FROM DUMPSITES AND RICE PLANTATIONS USING A BESPOKE LOW-COST UNIT IN ILE-IFE AND OKEMESI-EKITI, SOUTHWESTERN NIGERIA

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ABSTRACT

Compared to carbon dioxide (CO_2), methane (CH_4) is a more potent greenhouse gas, trapping more heat than CO_2 on a per molecule basis. With increasing levels of activities in prominent sources of methane such as livestock farming, rice farming and waste management, especially in developing economies like Nigeria, the need for a comprehensive and reliable CH_4 inventory cannot be over-emphasized. Using a bespoke low-cost measuring unit, this study investigated the vertical profile and variability of methane around rice farms and waste dumpsites. Findings show that ambient levels of methane around the rice farms ranged between 26 ppm and 698 ppm and were highest at temperatures >30°C while lower concentrations were measured at lower temperatures. High methane concentrations were observed at a height of around 15 m and gradually decreased with increasing altitude. For waste dumpsites, methane levels measured ranged between 45 ppm and 1220 ppm aligning with variation in the amount of waste. These higher concentrations are, however, often found at low altitudes below 20 m over both dump sites. At temperatures above 30 °C, methane concentrations are found at its highest across both dumpsites. Also, while waste dumpsites seem to emit more methane than rice farms, all study sites emitted appreciable amounts of methane which could accumulate and contribute significantly to regional climatic variations and enhance levels of tropospheric ozone. This study concluded that the bespoke measuring unit performed relatively well, and air temperature has a positive influence on methane concentration at all study sites.

Keywords: Low-cost sensors, Methane, Waste dumpsite, Rice plantation, Methane vertical profile, Bespoke measuring unit.

INTRODUCTION

In the early 1900s, atmospheric methane concentration remained almost constant until the beginning of the industrial age when a significant increase in atmospheric levels of methane began (Mohajan, 2012). Studies, for example, Reay *et al.* (2018), Sun *et al.* (2017) and Chukwuocha *et al.* (2011) have affirmed that global atmospheric methane concentrations have doubled since the start of the industrialization age. The increase in methane emissions from anthropogenic activities has proven to be one of the major causes of extreme weather conditions occasioned by global warming because of the relatively higher global warming potential (GWP) of methane (Sun *et al.*, 2017; Mohajan, 2012; Kavitha and Nair, 2019). The continuous and significant increase in atmospheric concentration of methane is a cause for serious concern and proactive steps need to be put in place to understand the nature and capacity of the major contributing sources (Javadinejad *et al.*, 2019).

Methane is known to cause health issues in animals, premature human deaths and reduced crop yields which leads to famine when concentration is above 1000 ppm (Prasad *et al.*, 2011; Mar *et al.*, 2022). It is an asphyxiant that displaces oxygen in the human body and when there is high displacement (18% and above), such an individual will be affected by asphyxia (Oguntoke and Adeyemi, 2017). Methane also affects air quality as it plays a central role in influencing stratospheric ozone and water vapour levels. It affects the atmosphere by increasing the concentration of water vapour and it plays a key role in the conversion of reactive chlorine to less reactive hydrogen chloride in the stratosphere (Keppler *et al.*, 2006). Furthermore, methane contributes to the formation of ground-level ozone which is also a dangerous pollutant that harms the ecosystem. Methane also reduces the

amount of hydroxyl ions available for the removal of other pollutant types in the atmosphere (Isaksen *et al*., 2014).

To understand the impact of methane gas on the atmosphere, environment, and global climate as a whole, there is the need to identify prominent sources of methane and quantify their contributions to atmospheric loading of methane. Apart from being a greenhouse, methane is also a major precursor of tropospheric ozone, which is termed "Bad Ozone".

Methane as a Greenhouse Gas (GHG)

Methane is the second most prevalent and potent greenhouse gas (after carbon dioxide) found in the atmosphere (Van Amstel, 2012). Greenhouse gases are the major cause of global warming as they trap heat emitted from the earth surface in the form of infrared radiation in the atmosphere; thereby causing a rise in the planet's average atmospheric temperature (Regmi, 2014). Greenhouse gases - carbon dioxide, methane, nitrous oxide – are all well known for their ability to trap heat and disperse both incoming and outgoing in the atmosphere (Dessus *et al.* 2008; Kweku *et al*., 2018). The ability of a greenhouse gas to trap heat is termed Global Warming Potential (GWP) and it is defined as the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (IPCC, 2013). Methane, however has a higher GWP than carbon dioxide ranging between 28 to 40 over a 100-year horizon causing it to absorb thermal infrared radiation much more efficiently than carbon dioxide (Mohajan, 2012; IPCC, 2013, 2014; Zhao *et al*., 2019; Winterstein *et al*., 2019; Aldhafeeri *et al*., 2020; Orji *et al*., 2020). Methane also contributes to global warming through infrared absorption and it controls the lifetime of other gases such as ozone in the atmosphere (Heilig, 1994).

Methane is known to have a short residence time (atmospheric lifetime) of 9 years but has an effective perturbation of 12 years which is relatively short when compared to other GHGs (Reay *et al*., 2018). Despite the short residence time in the atmosphere, the effect of methane in the atmosphere cannot be ignored as it causes severe global warming that in turn affects the climate (Mohajan, 2012).

Sources of Methane

Methane is emitted through different sources which are generally classified as both natural and anthropogenic sources (Jacob *et al*., 2016; Dean *et al*., 2021). Natural sources of methane include oceans, wetlands, termites, geological sources, wildfires and wild animals (Jardine *et al*., 2004; Van Amstel, 2012; Reay *et al*., 2018). According to Askyutin *et al.* (2018) and Van Amstel (2012), the highest natural source of methane is marsh systems/wetlands. Generally, natural sources contribute up to 37% of global methane emissions (Jardine *et al*., 2004).

Anthropogenic sources of methane include fossil fuels, agricultural practices, livestock/animal rearing, landfills, biomass burning, wastewater, and the oil and gas sector (Van Amstel, 2012). Anthropogenic sources contribute around 60 - 65% of global atmospheric methane concentration emissions (Jardine *et al*., 2004). The rapidly growing activities of humans, especially in agriculture, fossil fuel usage and waste disposal has led to an increase of anthropogenic methane emissions. Methane emissions are influenced by different factors such as energy use, human population distribution, agricultural practices and climate (Wuebbles and Hayhoe, 2002).

Emission of methane from rice cultivation and waste dumpsite

With an annual contribution of 23-34 *Tg* (~10% of total anthropogenic emission) to atmospheric methane (Jackson *et al*., 2020), rice cultivation is one of the prominent anthropogenic sources of methane, especially in the agricultural sector. (Naser *et al*., 2007; Khalil *et al*., 2008; Reddy *et al*., 2013; Smartt *et al*., al., 2016; Wang *et al*., 2018). Rice is the world's most important wetland food crop and there is an increasing demand for rice as the world population is on the increase (Anand *et al*., 2005; Humphreys *et al*., 2019). Just like natural wetlands, flooded rice fields cut off oxygen supply from the atmosphere to the soil which then leads to the anaerobic decomposition of soil organic matter (Neue *et al*., 1996). Equation (1) gives the overall chemical equation for the anaerobic decomposition of organic waste to yield methane:

$C_6H_{12}O_6$ $3CH_4 + 3CO_2$ + by-products (1)

During anaerobic decomposition, microorganisms break glucose down into methane (CH_4) and carbon dioxide (CO_2) as well as other byproducts such as water and organic acids.

Series of researches have been carried out on the emission of methane from rice, especially in wetlands, in China (Wang *et al*., 2021), Thailand (Yagi *et al*., 1994; Chareonsilp *et al*., 2000), India (Anand *et al*., 2005) and the United States of America (Bachelet and Neue,1993; Smartt *et al*., 2016; Sun *et al*., 2017; Humphreys *et al*., 2019; Sun *et al*., 2020). However, there has been little or no significant data of methane emission from rice fields in Africa (Akinbile *et al*., 2016), especially from Nigeria, the leading producer of rice in Africa with >8 million metric tonnes produced in 2021 (FAO, 2022).

Methane could be released from rice farming in three major ways - ebullition from land surface, diffused transport through the aerenchyma system of the rice plant and through diffusion loss (Jain *et al*., 2004).

When a field is flooded, methane is often trapped in the soil and under further amendments such as addition of organic matter, small amounts of methane is emitted through the ebullition process (Neue, 1993). Methane is also emitted from rice fields during the cropping season through its diffusive transport through the aerenchyma system of the rice plants and this account for over 90% of methane emission during cropping season (Jain *et al*., 2004). When soils become saturated with water, the exchange of gases is hindered, leading to a consequent loss through diffusion, resulting in the emission of methane (Jain *et al*., 2004).

There is a need to estimate methane emissions and reduce uncertainties because of the high emissions from rice paddies. Currently, in Sub Saharan African countries such as Nigeria, quality data on rice cultivation and its impact on greenhouse gas emissions is not readily available because of inadequate research arguably brought about by non-availability of monitoring equipment and technological know-how (Boateng *et al*., 2017; Akinbile *et al*., 2016).

Methane Monitoring and Measuring Methods

Methane emission poses environmental threat to the atmosphere and this suggests a need to ensure that sources of methane emissions are constantly tracked and documented for climate change mitigation purposes (Montzka *et al*. 2011; Daugela *et al*. 2021). Measurement of methane emissions is essential for improved understanding of processes that lead to emissions, detect regional trends in emissions and also develop robust emission inventories. Several methods have been developed and deployed to measure ambient level of methane:

Enclosure (Chamber) techniques

A number of studies (for example, Neue *et al*. (1996), Naser *et al*. (2007), Akinbile *et al*. (2012), and Humphreys *et al*. (2019)) used a closed gas chamber technique with a sampling bag for collection and portable gas analyzer for methane and other gases. Static and dynamic chambers are used to quantify emissions either by using the change in methane concentration per unit area (small areas) or by using the external flux gas known rate. However, single enclosures may not capture all variability in emissions and it also requires labour to measure the variability of emissions over large sources.

Micro-meteorological techniques

This involves the use of tower based vertical measurements and atmospheric parameters with standard modelling to calculate fluxes. Examples of these techniques include eddy covariance (Xu *et al*. (2014); Li *et al* (2018); Irvin *et al* (2021)), flux gradient (Edwards *et al*., 2001), amongst others. The eddy covariance technique measures total methane emissions from individual sources continuously over time to capture temporal trends. There is over and under estimation of methane emissions since it is difficult to measure the variability. One major disadvantage of the eddy covariance technique is that the measured values are an area average making it rather difficult to identify specific processes and sources of methane emission (Chaichana *et al*., 2018).

External tracer

Czepiel *et al*. (2003) used tracer method to calculate the total landfill methane emission rate. This is the release of tracer gas at a known rate from source areas. It measures complex sources or quantifies uncertainty in the emission estimate. It is difficult to isolate individual sources within source area depending on the layout and it also needs the right meteorological conditions necessary for the proper functioning.

Satellite

Several studies (e.g., Jackson *et al*. (2020) and Javadinejad *et al*. (2019)) have used satellite data from Greenhouse Gases Observing Satellite (GOSAT) and Moderate Resolution Imaging Spectroradiometer (MODIS) to analyse methane fluxes from satellite observation. This provides global, complete spatial coverage and frequent revisit time with a single instrument. It is not as accurate as in-situ data and emissions are not cleanly resolved. It is also limited by sunlight, cloud cover and snow free scenes.

Low-cost sensor devices

An alternative and relatively cheaper way of measuring methane is the use of low-cost sensors which could be assembled to create devices to measure methane concentration. Low-cost sensor technology, whose application and accuracy has improved significantly in the last decade due to improved technology, has the capacity to provide more accurate paddy field data (Sun *et al*., 2017). Daugela *et al*. (2021), Yang *et al* (2019) and Cheng *et al*. (2018) used MQ4 gas sensor to measure methane concentration while Montoya *et al*. (2020) and Nagahage *et al*. (2021) created a monitoring device that could measure carbon dioxide and methane using MOS sensors.

Advantages of using low-cost sensors in measuring methane concentrations cannot be over-emphasised. It has helped scientists, especially in developing economies, to overcome the age long challenges of inability to take measurements over a long period of time due to a myriad of problems including expensive cost of reference research-grade devices. These challenges have shown the need to develop more relatively cheaper, handy (less bulky) and low-energy consumption low-cost sensor devices to help in monitoring atmospheric pollutants, especially in developing economies. It is also important to emphasise that low-cost devices can provide a wider network (spatial) and has the potential to serve as a reliable fast methane analyzer (Bastviken *et al*., 2020; Nagahage *et al*., 2021).

DATA AND METHODOLOGY

Study Site Description: Rice Farms and Waste Dumpsites

Sampling of methane on rice farms was carried out in Ekiti State, a choice influenced by the state's position as one of the major cultivators of rice in southwestern Nigeria. Precisely, the selected rice farms are located in Okemesi-Ekiti, a town in Ekiti-West local government. Okemesi-Ekiti is a rural agro-town with rich fertile soils enabling extensive arable farming. Two rain-fed rice farms were considered in this study and are both located in Okemesi Ekiti. The coordinate of the Rice Farm-A (RF-A) and the Rice Farm-B (RF-B) are (7.88°N, 4.94°E) and (7.88°N, 4.95°E), respectively. See Figure S1 in the supplementary material document for pictures of a section of each of the two rice farms.

The rice farms are located about 7 km apart and similar agricultural practices are adopted on both farms except that the population of rice stalks, soil type, and farm area differ from one another. Rice seeds were planted in July through direct seeding and are able to germinate on the soils through adequate flooding of the soil just at the beginning of the rainy season.

The two selected waste dumpsites are located within the estate of the campus of the Obafemi Awolowo University, in Ile-Ife, Osun State, Nigeria. The two dumpsites are located on the campus of the Obafemi Awolowo University, Ile-Ife. The first of the dump sites, Waste Dumpsite-A (WD-A) is located in Tonkere (7.53°N, 4.53°E), a remote village within the University. WD-A receives all types of waste - residential, commercial and institutional wastes, as it serves the local Tonkere village communities and the University including the staff quarters. Every waste generated in the University is disposed of

and sorted at this site. The second dumpsite, Waste Dumpsite-B (WD-B) (7.52°N, 4.51°E) is a commercial (market) dumpsite where all wastes from commercial activities are deposited daily (See Figure S2). This is located in the market area of the campus where students and staff get their daily needs ranging from vegetables, groceries, raw and cooked foods etc.

Bespoke Methane Measuring Unit and its Calibration

The development of the bespoke methane measuring unit used in this study was done by procuring and programming low-cost sensors onto an Arduino Uno microcontroller board. These low-cost sensors (LCS) were programmed to measure specific atmospheric parameters. The collection of LCS programmed includes:

- MQ-4: This is a gas detector sensor which is responsible for measuring methane gas concentration and it is calibrated to take readings in parts per million (ppm). It has high sensitivity to methane and can measure concentrations up to 10,000ppm.
- LPS22HB: This is a barometric sensor module; it has an in-built temperature sensor and measures both atmospheric pressure and ambient air temperature.
- GPS Module: This is responsible for providing data on the latitude, longitude, and altitude above sea level.
- Micro SD Card Module: It supports the micro-SD card which aids data logging at various programmed intervals.
- DS3231 RTC Module: A real-time clock that counts seconds, minutes, hours and the date when measurements were taken.

The arrangement of the pins of the component LCS unit is as shown in the schematic diagram presented in Figure 1.

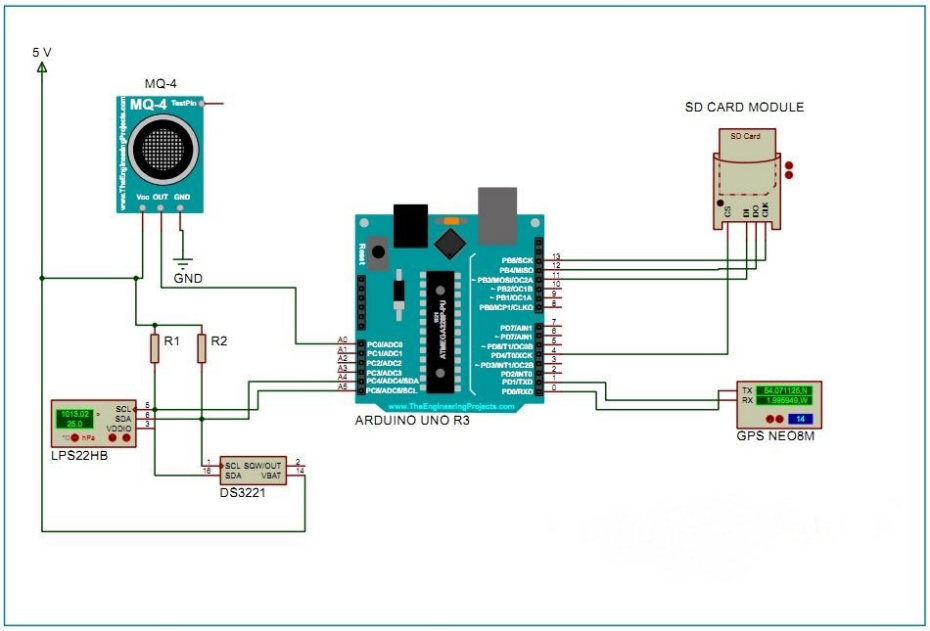

Figure 1: A schematic diagram of the Low-Cost bespoke measuring device showing the connection of the LCS.

The datasheet for each sensor was used in programming the sensors onto the Arduino board. The sensors were first tested on a breadboard before they were transferred to the Arduino. The codes written for each sensor are then run to instruct the sensors on the task to perform. The sensors were arranged in a waterproof box such that there were no obstructions to the measurements as shown in Figure S3(b). The antenna of the GPS module was carefully placed to face outwards, just as for the MQ4 sensor and the LPS22HB sensor. The Arduino board, SD Card module and RTC module were placed in the box alongside the batteries used to power the device. The device can be powered by a power bank via the use of a USB

cable or through the use of external batteries (See Figure S3 for pictures of the external and internal views of the bespoke LCS measuring unit). The constructed unit can be deployed as a stationary wireless sensor network or mounted on an unmanned aerial vehicle (UAV). However, in this study, the device was deployed over the study sites using a drone.

It is important that portable monitors are subject to calibration checks at least as much as reference analysers (Masey *et al*., 2018). The constructed device was calibrated using Aeroqual S-500, a near-reference industry standard gas monitor. These are relatively compact and lightweight (460 g), and can be operated from an in-built battery (for 8 hours) or from mains power. The readings from both the constructed bespoke unit and Aeroqual monitor were recorded in parts per million (ppm). Readings were averaged into 10 minutes intervals and a graph of methane concentration from Aeroqual and the constructed device were plotted against each other. A linear fitting was carried out on the plotted graph.

The graph of the calibration curve for the LCS device is shown in Figure S4. The calibration result was then used to calibrate the constructed bespoke unit. The correlation coefficient (R-squared) value of ~0.77 shows that the constructed device had a good fit with the near-reference Aeroqual monitor. The data in the calibration curve shows that the bespoke measuring unit can perform quite well in relation to the Aeroqual air monitor, and both techniques can provide consistent methane emission results.

Deployment of the Bespoke Methane Measuring Unit for Sampling

The bespoke measuring unit was deployed with the use of a Fimi X8 SE2020 drone. The Fimi X8SE 2020 drone weighed ~765g while the device weighed around 480g; this made it possible for the drone to conveniently lift the device over a period of time. With the device attached to the drone, it had a total flight time of 30 minutes on average. The Fimi X8SE 2020 drone application was downloaded from Google Play store and installed on a mobile phone. The drone was monitored and controlled using the set-up controller and mobile phone.

In this study, the bespoke low-cost measuring device was attached to the drone (See Figure S5(a)) and flown over the rice farm and the dumpsite at different altitudes (Figure S5(b)). An altitude is maintained for about 5 minutes before it is moved on to another height. During its stay at a particular altitude, the drone hovers around the whole area measuring and recording methane concentrations over that area and at that altitude. The altitude probe of methane concentration was undertaken to investigate the possible variation of methane concentration with height.

The measurement period at the two rice farms was three months: 18 September - 30 November 2021. For the Waste Dumpsite-A, methane was sampled between 18 October and 15 November while for the WD-B, the period is between 21 September and 8 November, 2021.

Data Analysis

Air was sampled live onboard the drone and the obtained data was stored on the SD card attached to the measuring device. The readings were saved in a comma separated format in a text file before being imported into a Microsoft Excel spreadsheet. The averaging of the parameters (height, temperature and methane concentration) was taken in order to account for different altitudes. A 3-D colour fill plot was generated to show the relationship between temperature, methane concentration and height. This step was repeated for all the days of measurement and in all the study sites. Statistical analysis was done with Origin 2018 software and Microsoft Excel.

RESULTS AND DISCUSSION

Methane Emission from the Rice Farms

The rice planted on the rice farms used in this study was done through direct seeding on the fields. The fields were previously flooded before the seeding process. Measurement of methane on the rice fields started 59 days after the completion of the planting process. The study covered the reproductive phase of the rice plants starting from the transplanting stage and ending at the harvest stage.

Figure 2 shows there is an obvious variation in

methane concentrations with altitude as distinct concentration tiers can be observed. On Rice Farm-A (Figure 2(a)), during the reproductive phase, methane concentrations decrease with increasing altitude. Altitudes below 15m are observed to have high methane levels up to around 698.0 ppm while altitudes of 15-30 m show average concentrations of up to 503.0 ppm and concentrations in altitudes above 30 m are in the low range of around 25.0 ppm. Variations occur, with sporadic low concentrations above 20m initially and towards the end of the study. Methane concentrations decreased gradually as rice crops progressed from vegetative growth to harvest. Peak concentrations of 696.72 ppm, 648.26 ppm, 626.60 ppm, and 506.26 ppm were noted during the vegetative, flowering, maturity, and harvest stages, respectively. This decline is attributable to diminishing moisture content of the soil due to reduced rainfall occasioned by the onset of the dry season. Although Rice Farm A possesses a higher water retention capacity, the decrease in flooding before harvest, as noted by Naser *et al.* (2007), could have contributed significantly to the observed reduction in methane emissions.

Also, on the Rice Farm-B (Figure 2(b)), methane concentrations decrease with increasing altitude, though the trend seems to cease towards the end of the study period. Initially (within the first 100 days), altitudes below 15 m have concentrations as high as 592.0 ppm, while at altitude of 20 m and below show averages of up to 445.6 ppm. Altitudes above 20 m demonstrate low concentrations in the range of 25.0 ppm - 277.4 ppm. Towards the end of the study, average concentrations shift from below 10 m to low concentrations at all altitudes. The study indicates that as the rice matures with progressing days, methane concentrations decrease, particularly at altitudes above 20 m. This research highlights, especially in the tropics, that methane concentrations are highest at lower altitudes (below 15 m), with a noticeable shift from high to extremely low concentrations as altitude increases, emphasizing the possible significant roles of methane emission and atmospheric dynamics in upward diffusion.

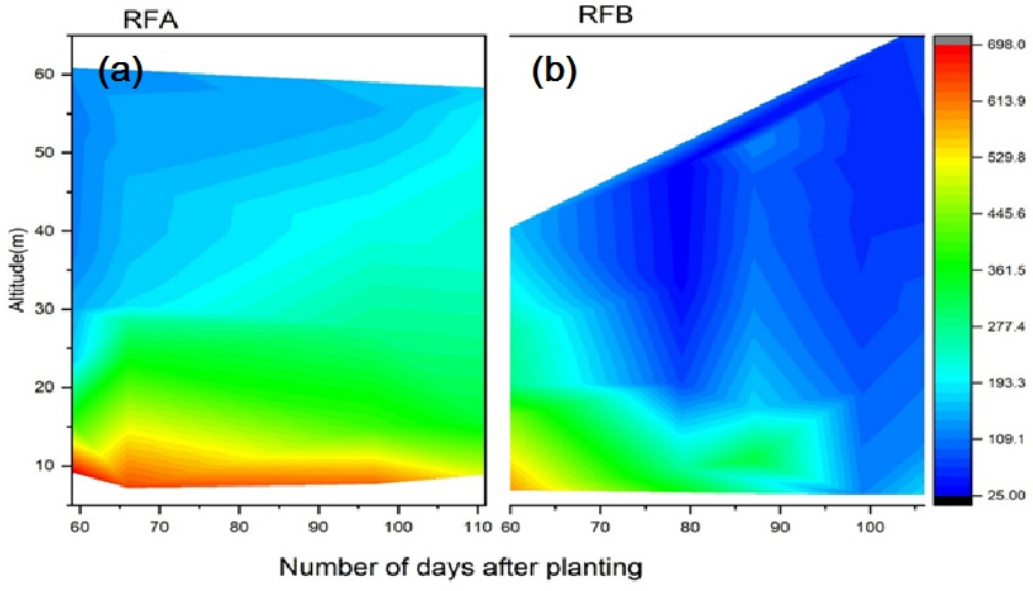

Figure 2: A 3-D plot of methane concentration, altitude and number of days after planting for: (a) Rice Farm-A (RF-A) and (b) Rice Farm-B (RF-B).

Overall, high concentrations are near the surface, average concentrations in the mid-range, and low concentrations at higher altitudes.

On the Rice Farm-A, methane concentrations presented in Figure 3(a) reveal a positive correlation with temperature. Higher temperatures, particularly in the range of 32 °C to 38 °C, coincide with dominant high methane concentrations > 500 ppm. Towards the end of

the study period, traces of high concentrations extend up to 41 °C. At the start of measurement, average concentrations (280 ppm and 500 ppm) are seen between 30.0 °C and 32.2 °C, but these shift to higher temperatures above 38.0 °C as the study progresses. The later phase of the study observes average concentrations prevailing from 30°C to 42 °C. Temperatures below 30 °C correspond to low methane concentrations < 250 ppm, and this is also observed towards the end of the study at temperatures up to 38 °C.

On the Rice Farm B (Figure 3(b)), at the commencement of the study, high methane concentrations > 500 ppm were observed at temperatures of 34 °C to 36 °C. Average concentrations (300 ppm to 500 ppm) were also observed at 32 °C to 36 °C at the beginning of the study. However, as the rice plants approached maturity through the course of the study, the level of concentration decreased as low methane concentrations < 250 ppm were dominant at temperatures between 26 °C to 36 °C. This pattern is attributed to suboptimal vegetative growth at RF-B, leading to reduced emissions.

Both farms consistently exhibit low methane concentrations < 250 ppm at temperatures below 30 °C throughout the study (Gaihre *et al.*, 2011), corroborating the positive impact of air temperature on methane emissions (Javadinejad *et al.*, 2019; Sun *et al.*, 2020). Methanogenic bacteria tend to have optimal rates around 30°C, and higher temperatures above this threshold enhance methane emissions (Jain *et al.*, 2004; Gaihre *et al.*, 2011; Smartt *et al.*, 2016). The study asserts that temperature plays a role in methane emissions from these rice farms, impacting both the concentration levels, the behaviour of methane-producing bacteria and vertical dispersion of emissions.

Generally, factors which influence the emission of methane from rice farming include soil factors, organic matter, rice straw addition, environmental factors (such as biomass accumulation and cultivar selection, rice field expansion and increased fertilizer usage) (Smartt *et al.*, 2016; Rajendran *et al.*, 2024) and soil variables (such as temperature and soil saturation status, pH, sulphate concentrations). Others are ability to manage water, organic amendments, fertilization, cultural practices and rice cultivars (Neue *et al.*, 1996). A combination of two or more of these factors could have influenced the variation of methane emission from the rice farms even though the same type of rice seeds and propagation methods were used on the two rice farms.

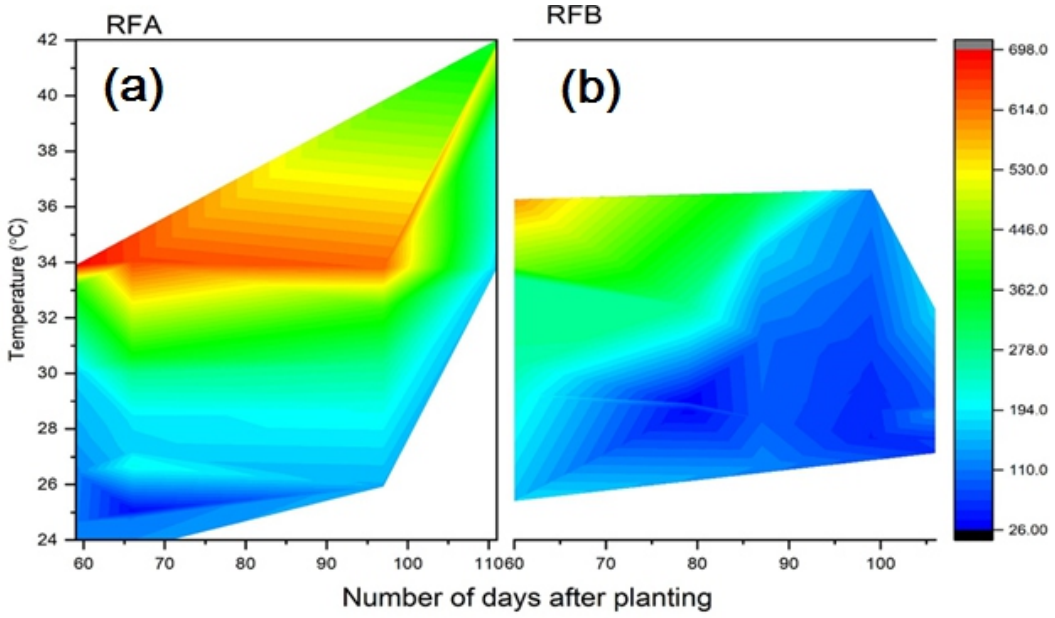

Figure 3: A 3-D plot of methane concentration, temperature, and number of days after planting for: (a) Rice farm A (RF-A) and (b) Rice farm B (RF-B).

Methane Emission from the Waste dumpsite

From Figure 4, it can be observed that at the commencement of the study for Waste Dumpsite-A (WD-A) (Figure 4(a)), average methane concentrations ranging between 500 and 900 ppm were found at altitudes less than 10 m and they progressed up to 22 m in the course of the study. Traces of average methane concentration were found after about 10 days up to a height of 50 m. High methane concentrations (930 ppm to 1150 ppm) were observed towards the end of the study at altitudes less than 12 m. Low methane concentrations were found at altitudes above 10 m at the beginning of the study and towards the end of the study, it was found at altitudes higher than 20 m.

Also, from Figure 4(b), at Waste Dumpsite-B (WD-B), high methane concentrations are found dominant at altitudes <10 m at the beginning of the study. Average concentrations are found in traces at altitudes between 10 m and 12 m. As the study progresses, average concentrations were dominant at altitudes <10 m up to about 20 m. Towards the end of the study, high concentrations are found at altitudes less than 12 m. However, there are traces of high concentrations found at altitudes up to 20 m at the end of the study. Average concentrations are also seen in traces at altitudes above 25 m. Above the average concentration, low methane concentrations are found at altitudes above 15 m at the beginning of the study and above 30 m as the study progresses.

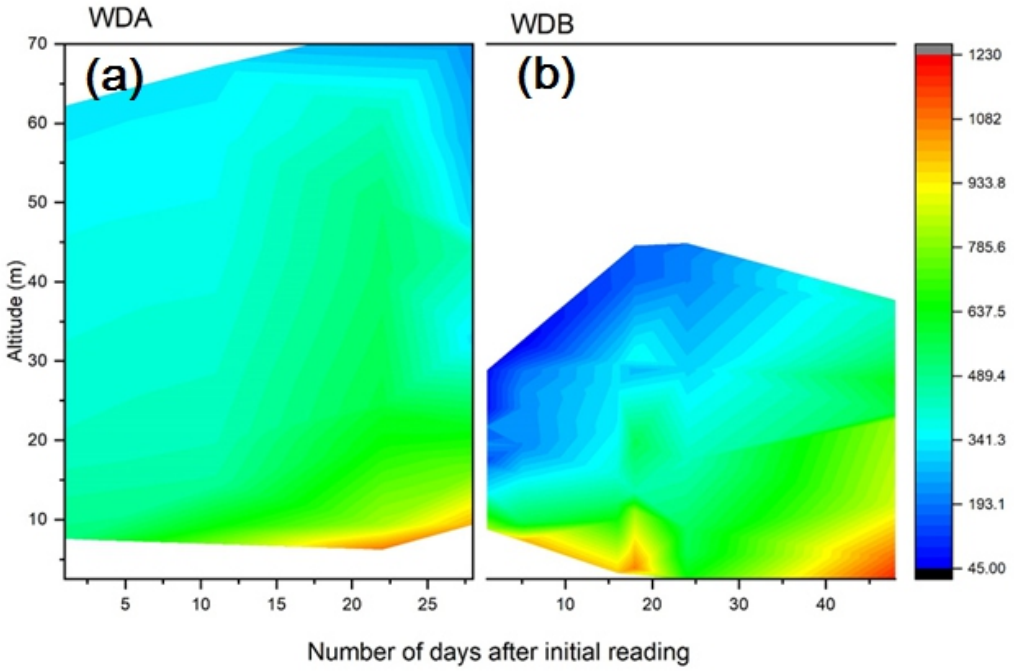

Figure 4: A 3-D plot of methane concentration, altitude, and number of days after initial reading for: (a) Waste Dumpsite A (WD-A) and (b) Waste Dumpsite B (WD-B).

Methane emissions from different dump sites show that methane is found in high concentrations irrespective of its location. This high concentration is however often found at low altitudes below 20 m for both dump sites. This can be attributed to the dominance of high methane concentrations that are found at point sources (closer to the ground where waste is being disposed).

At WD-A, during the start of the study, average methane concentrations (490 ppm to 850 ppm) are found at high temperatures for each day with a range difference of 1°C measured (see Figure 5(a)). As the study progresses, concentrations ranging from 800 ppm to 1150 ppm are observed at temperatures from about 33 °C to 43 °C, although traces of average concentrations are found at about 27°C. Towards the end of the study, high concentrations were found at about 32 °C to 40 °C. Low concentrations < 380 ppm are found immediately after the average concentrations recorded all through the study. These low concentrations are dominant at

temperatures less than 35 °C at the beginning of the study and less than 30 °C towards the end of the study.

Also, from Figure 5(b), at the WD-B, high methane concentrations (890 ppm to 1150 ppm) are found both at the beginning and towards the end of the study at temperatures higher than 34 °C. Average concentrations are found at temperatures between 32 °C and 34 °C at the beginning of the study. As the study progresses, average concentrations dominate at high temperatures from about 32 °C up to 50 °C. Low methane concentrations < 350 ppm are found at temperatures less than 32°C and there are traces of low methane concentrations even at temperatures up to 45 °C on the 25th day.

It is shown from both dumpsites that as temperature decreases, methane concentration decreases throughout the study. The highest methane concentration measured on each day is often found at high temperatures measured for the day also. This finding corroborates the fact that barring other factors like composition of emission source, there is always a positive correlation between methane emission and ambient and source temperatures (Granberg *et al*., 2001; Zhu *et al*., 2021).

Inter- and intra-comparison of methane emission from the Rice Farms and Waste Dumpsites

The magnitude of methane emissions from rice farms is as a result of complex and dynamic interactions among the plants, microorganisms and the environment. Therefore, emissions from different rice farms may differ from each other depending on different factors (Jain *et al*., 2004). According to Gaihre *et al*. (2011), there are considerable spatial variations in methane emission rates even across nearby fields and they are majorly influenced by soil properties susceptible to temporal variations. The spatial and temporal variations are also related to rice biomass, which is a function of cultivar and soil dependent property (Jain *et al*., 2004).

The emission of methane gas from waste dumpsites is dependent on the operational activities of the dumpsite such as the thickness of daily deposition, the provision of daily cover, temperature and production process. These processes result in emissions that vary with time of the day and year (Zhao *et al*., 2019; Bakkaloglu *et al*., 2021; Schirmer *et al*., 2014).

Methane is lighter than air, hence it is expected that it tends to move upwards through landfill surface. It can however be inhibited by daily cover as methane diffuses out to surrounding areas in lower concentration. It can be observed from the above plot that at WD-A, there is a higher diffusion rate when compared to WD-B. This is due to the fact that waste is brought into the WD-A regularly and are dumped randomly at areas of their choices, however, methane diffuses into other areas without new top cover. For WD-B, it has a small size and hence daily top covers are expected to inhibit the concentration of methane that diffuses into higher altitudes. At high altitudes, methane concentrations were still close to average (500 ppm to 900 ppm) for WD-A while for WD-B, at altitude higher than 27 m, there were already extremely low concentrations < 470 ppm.

In this study, methane concentrations were found to be highest at dumpsites compared to rice farms which are probably due to the high organic matter content of the dumpsites. Concentrations reached up to 1085.21 ppm at dumpsites while the highest methane concentration recorded over rice farms was around 696.72 ppm. Although, despite the difference in the quantity of methane emitted from both site-classes, for most days of measurement, methane concentration decreased with an increase in height but increased with increase in ambient air temperature. For the study sites (rice farm and waste dumpsite), high concentrations of methane are found at a range of high temperatures recorded on the sites and as temperature decreases, methane concentration decreases also. Also, all study sites emit quantifiable amounts of methane which could over time accumulates and cause damage to the global climate. These sites are representative of emissions from two of the identified prominent sources of methane, especially in tropical developing economies.

CONCLUSION

At rice farms, methane concentrations are found

to be highest at low altitudes and as temperature increases, methane concentrations increase. This is, however, influenced by the atmospheric dynamics that created changes in the diffusion of methane into the atmosphere. Methane emissions from rice farms are influenced by a variety of factors such as plant biomass, air temperature, vegetative growth, water management/regime, soil type, and the presence of soil organic matter. Methane emissions from rice farms are also influenced by human activities such as ploughing of rice straws from previous planting seasons and the application of fertilizers on rice farms.

A variation of about 500 ppm was found between days with high and low quantities of waste. Waste dumpsites are great emitters of methane as high concentrations are recorded on both dumpsites. Emissions from dumpsites are affected by the presence of daily top cover, quantity of waste generated, and operational activities of the site. Although the WD-B showed higher methane concentration at ground-level than WD-A, this can also be attributed to the composition of the organic refuse and the types of waste found at both sites. More organic wastes are found at WD-B such as food waste, fruits, rotten vegetables, human feaces amongst others. This can be responsible for the high concentration observed at ground level.

One of the limitations of this study was a stringent budget under which it was carried out. As such, the scope of investigation could not be more robust. Further steps could be taken to investigate other factors that could influence methane emissions from rice farms and waste dumpsites in a tropical monsoon climate.

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AUTHORS CONTRIBUTION
PO contributed to the study design, sensor development, fieldwork, data analysis and drafting the first draft, OGF contributed to the study design, fieldwork, supervision of fieldwork, data analysis and preparation of the first and review of the manuscript, OEA contributed to the study design, sensor development, fieldwork and data analysis, LAS contributed to the supervision of fieldwork and revision of manuscript and ABA contributed to the development, calibration and deployment of the sensor.

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