# Assessment of Greenhouse Gas Emissions from Onsite Sanitation Systems: Flux Chamber Design and Field Methodology

Olivia Reddy[1], Prativa Poudel[2], Cynthia Kusin Okoro-Shekwaga[3], Abraham Geremew[4], Anish Ghimire[3], Baba Ngom[5], Kenan Okurut[6], Barbara Evans[3], Guy Howard[1], *Miller Alonso Camargo-Valero[3]

[1] School of Civil, Aerospace, and Mechanical Engineering, University of Bristol, United Kingdom

[2]Department of Environment Science and Engineering, Kathmandu University, Nepal

[3]School of Civil Engineering, University of Leeds, United Kingdom

[4]College of Health and Medical Sciences, School of Science, Haramaya University, Ethiopia

[5]École Polytechnique de Thiès, Senegal

[6]Department of Building and Civil Engineering, Kyambogo University, Uganda

* Corresponding Author: m.a.camargo-valero@leeds.ac.uk

## Abstract

Projected quantities of greenhouse gas emissions from onsite sanitation systems vary considerably depending on the methods used. There is a need to use empirical field data to form the base of more robust, global estimates. Current methods are laboratory heavy and require expensive equipment, thus limiting the amount of data that can be collected in rural areas, and by those in low- and middle-income countries. These methods were evaluated, and a key piece of equipment, the flux chamber, was redesigned. Through both laboratory work and field trials, the new flux chamber, which repurposes landfill and contaminated land portable gas analysers, was able to deliver real-time results for carbon dioxide and methane from onsite sanitation systems. This paper successfully demonstrates these new field methods for evaluating GHG emissions from onsite sanitation systems, including tanks and pit latrines.

**Keywords:** sanitation, greenhouse gases, onsite sanitation, flux chamber, emissions

## 1. Introduction

Access to piped sewer systems is not the global norm. Where access to funds, space, and water is limited, onsite sanitation is a useful method for containing and treating human excreta. Currently, around 3.2 billion people are served by onsite sanitation, accounting for 43% of the global population (JMP, 2021). The population connected by onsite sanitation is ever-increasing, especially in low- and middle-income countries (LMICs). As of 2021, data shows that there is a trend of onsite sanitation systems over sewer systems in recent years (JMP, 2021).

Where emissions are concerned, human excreta produces carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) through biological decomposition processes (Diaz-Valbuena *et al.* 2011; Huynh *et al.* 2021). To date, the focus when quantifying GHG emissions from sanitation systems has come from centralised wastewater treatment plants, which can attribute to over 1.5% of total GHG emissions and approximately 5% of the total non-$CO_2$ GHG emissions (Dickin *et al.*, 2020). Due to

increased dependence and the widespread nature of onsite sanitation, there is, however, an increasing, but limited amount of GHG emission data from septic systems being reported, using both theoretical and field-based measurements (Diaz-Valbuena *et al.* 2011; Reid *et al.* 2014; Truhlar *et al.* 2016; Ryals *et al.* 2019; Somlai, Knappe, and Gill 2019; IPCC 2019; Huynh *et al.* 2021).

Sanitation is managed in a multitude of ways across different countries, but for LMICs, this can be broken down into basic sanitation across a spectrum of unlined, lined and sealed pits and tanks (often broadly described as 'pit latrines', or 'septic tanks'), and no sanitation/open defecation (JMP, 2021). Due to this broad range of onsite sanitation technologies, developing a means of quantifying emissions from such a varied group has been difficult. In fact, to date, most research on GHG emissions from onsite sanitation has come from septic tanks (Somlai, Knappe, and Gill 2019; Huynh *et al.* 2021).

It has been noted, that pit latrines produce a significant source of $CH_4$ emissions (Couderc *et al.* 2008; Reid *et al.* 2014; Kulak *et al.* 2017; Van Eekert *et al.* 2019), with the work performed by Reid *et al.* 2014 giving us a global prediction that 1% of the total $CH_4$ emissions occurs from pit latrines. Their methods used high-resolution geospatial analysis, including data on water table depth, combined with the region-specific BOD suggested by the IPCC guidelines. This was then supported by laboratory experiments analysing chemical oxygen demand (COD), total solids (TS), and volatile solids (VS). These results are invaluable; however, they do not use empirical data collected from pit latrines.

Defined as an enclosed volume over a surface that allows the collection and sampling of GHG that are to be measured and quantified (Eklund, 1992), flux chambers (FC) have been described as simple, flexible, and accurate measurement technique (Debra, 2014). Current FC methods, which have been used to collect GHG emissions data from septic tanks, require the gas to be collected in vials and transported to a laboratory where analysis can be performed using gas chromatography to determine the amount of GHG within the sample (Diaz-Valbuena *et al.* 2011; Huynh *et al.* 2021). Here, empirical data was collected successfully, but the use of the laboratory gives travel and sample size limitations, as well as limiting access to researchers in poorer, rural locations, where this work is most required. Overall, the minimal amount of empirical data currently available means that there is a need for a better, practical methodology for gathering GHG emission data from onsite sanitation systems.

Current estimates of GHG emissions from on-site sanitation are too few and provide varying results. With the number of communities connected by onsite sanitation ever-increasing globally, it is pertinent to determine the amount of GHG emissions that can be attributed to this. At present, the research in this requires strengthening the empirical data collection, using more inclusive methods (cost, equipment, urban/rural) for communities in LMICs to access. The methods presented in this paper have been developed to give a better overall view of the intricacies affecting sanitation and climate change, focusing on collecting robust, empirical data. This paper addresses the high levels of uncertainty (Cheng *et al.*, 2022) around the GHG emissions from onsite sanitation. Data generated using these methods can be added to inform current IPCC practices and paves the way for countries to include emissions more accurately from onsite sanitation systems into their nationally determined contributions (NDCs).

# 2. Materials & Methods

## 2.1. Modified Static Flux Chamber Design

To date, FC have predominantly been used in studies looking at GHG emissions from soils, whether from a landfill site or permafrost. This same technique can be applied to sanitation systems,

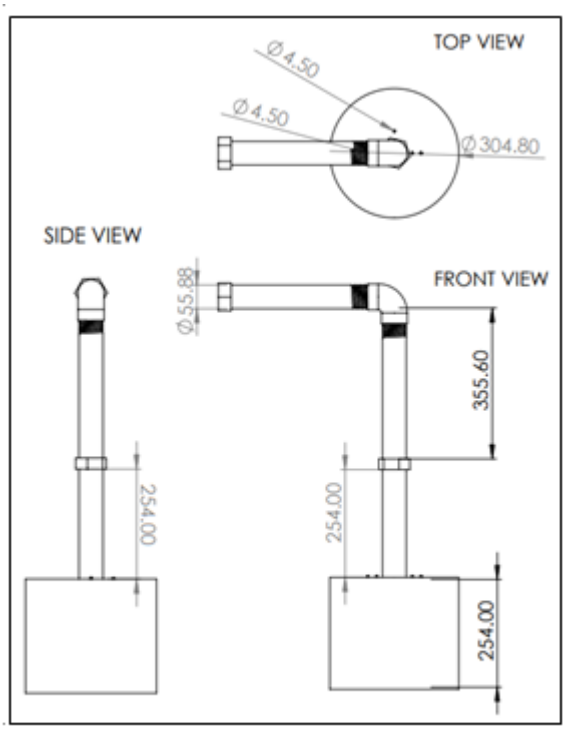


*Figure 1: Blueprint of open FC design, using Solidworks. The closed chamber looks like this without the vent pipe.*

The emission rate of gas ($E_{con.}$) from the whole containment (septic tank or pit latrine) is calculated as below:

$$E_{con.} = E_{FC} \times A_{con.}$$

Where, $E_{con.}$ Is the emissions rate of the whole containment (g/cap/day), $E_{FC}$ is the emission rate from the flux chamber (g/cap/day), and $A_{con.}$ is the surface area of the containment ($m^2$). This can easily be converted to per capita by dividing by the total number of people in a household.

The surface emissions from the flux chamber are calculated as:

$$E_{FC} = \frac{Q \times C}{A_{FC}}$$

Where, $Q$ is the volumetric gas flow rate ($m^3$/s or L/s), $C$ is the concentration of gas in the gas mix (g/l), and $A_{FC}$ is the cross-sectional area of the FC ($m^2$).

The flowrate, Q, can be calculated as:

$$Q = v \times A_{vent}$$

Where, $v$ is the flow velocity of the gas in the vent (m/s), and $A_{vent}$ is the area of the vent pipe ($m^2$).

The blueprint of the open FC consists of the main chamber and a connected PVC ventilation pipe (*figure 1*). Additionally, to lower the FC into the containment, a tripod with a rope pulley was used. Where it is possible to cover the hole in the chamber while using the FC, a clamp stand is used instead. The open flux chamber allows for continuous gas flow measurements, but to account for different gas flow rates and design conditions (onsite) a closed chamber method was also developed. Both systems were validated for their situations.

*Table 1: Materials used in the FC at each institution*

| Institution | Kathmandu University (Nepal) | University of Leeds (UK) | Ecole Polytechnique De Thiès (Senegal) | Kyambogo University (Uganda) | Haramaya University (Ethiopia) |
|---|---|---|---|---|---|
| Flux Chamber Material | Fibreglass | PVC | Plastic Bucket | UPVC | Fibreglass |
| Flux Chamber Diameter | 304.8mm and 152.4mm | 304.8mm and 152.4mm | 152.4mm | 152.4mm | 304.8mm and 152.4mm |
| Flux Chamber Headspace Volume | 5L | 5L | 5L | 5L | 10L |
| Vent Pipe Material | PVC | PVC | PVC | UPVC | PVC |
| Vent Pipe Diameter | 50.8mm | 40mm | 32 mm<br>50 mm | 50.8mm | 50.8mm |
| Rotameters Used | $CO_2$ and air | Air | $O_2$ rotameter<br>Gas compressor for air or $O_2$ | $O_2$ Medical gas/air regulator | $O_2$ rotameter<br>Medical gas regulator |
| Additional Equipment used | N/A | Air velocity: FLUKE 975 AIRMETER | GEM 5000<br>Spectro (AL800) | N/A | N/A |


*Figure 2: Using PVC diameter reducers in Uganda (left), drilling holes for tubing in Nepal (right).*

The main chamber (length =254mm, ⌀ = 304.8/152.4 mm) was prepared from non-reactive materials such as PVC or fiberglass. However, where this is not available, locally available plastic buckets or jerrycans, which have similar dimensions, can be used (*table 1*). The main chamber was sealed from one side while the other side was open to collect the gas over the surface.

A PVC ventilation pipe (⌀=50.8mm, length =254mm) was connected to the main body of the chamber, by drilling a hole in the sealed end of the main body and inserting it. Where PVC piping was used throughout the FC, diameter reducers were used to connect from the larger main body diameter to the diameter of the ventilation pipe (⌀=50.8mm) (*figure 2*). A hole was drilled into the ventilation pipe to allow access for the anemometer (Testo 50i). A tight-fitting cap was kept at the end of the chamber. The length of the connected pipe can be adjusted to suit different onsite sanitation systems by attaching additional PVC piping over the ventilation pipe in 355.6mm increments. An L-shaped elbow joint can be added to allow for better access to certain containments.

To overcome the need for both the use of a fan inside the FC (such as those used in Diaz-Valbuena *et al.*, (2010) and Huynh *et al.*, (2021)), and the need to travel to and use laboratory equipment, this FC method repurposes landfill gas analysers (GeoTech GA5000 and GeoTech G200) to collect GHG emission data immediately in the field. The chamber's main body is perforated at the top with five holes to allow the associated monitoring equipment (gas analysers, and manometer) to be connected with Teflon tubing (*figure 2*). Two holes are connected to the inlet and outlet of the gas analyser for $CH_4$ and $CO_2$ (GeoTech GA5000). The other two holes are connected to the inlet and outlet of the gas analyser for $N_2O$ (GeoTech G200). Connecting both the inlet and outlets allows for mixing of the gas inside the FC, ensures that the mass of gas is homogenized, and prevents a vacuum from being created. The remaining hole is used to connect the manometer (testo 511 Absolute Pressure Meter) to record the pressure inside the FC. After fitting, all holes were properly sealed to prevent any leakages.

## 2.2. Open Flux Chamber Principles

Calibration tests were undertaken in laboratories at the following institutions: Kathmandu University (Nepal), University of Leeds (UK), Ecole Polytechnique De Thiès (Senegal), Kyambogo University (Uganda), and Haramaya University (Ethiopia). Although every effort was made to ensure that the set-up was the same, we were limited by the equipment and materials available in each country. Different rotameters were used, as well as the test gases. Each rotameter was calibrated for the institutions test gas by using both a water displacement method with linear regression, and density conversations using the following equation:

$$Q_2 = Q_1 \times \sqrt{\frac{\rho_1}{\rho_2}}$$

Where, $Q_1$ is flow rate as measured by the rotameter ($m^3$/s or L/s), $Q_2$ is the actual inlet flow rate ($m^3$/s or L/s), $\rho_1$ is the density of the gas which is being measured ($g/m^3$) (at room temperature), and $\rho_2$ is the density of the gas which the rotameter is calibrated for ($g/m^3$) (at room temperature).

For flow-rate calibration, the anemometer records the volumetric flow rate in $m^3$/h or velocity in m/s, which is then converted to LPM. The flow rate from the gas mix and the recorded flow rate must be similar, with minimum marginal error, to ensure that the FC is working properly. Flow rate calibration was measured both before and after the elbow in the PVC vent, to determine if this influenced the data.

a) Gas analyser was disconnected from the FC. All unused tubing was properly sealed, then disconnected from the mixed-gas rotameter to the FC; b) Manometer and anemometer were set-ups; c) Air compressor was turned on and set to a known flow rate on the airflow rotameter; d) The tube from the mixed-gas rotameter to the FC was connected, and the timer and anemometer started; e) Time taken to get a reading on the anemometer was recorded; f) Velocity and volume flow rate of the gas mixture through the pipe was measured.

The FC was lowered into the containment (pit/tank) with the gas analysers and the vent pipe attached. Once settled, the concentration of gases and the flow rate from the vent pipe are measured at regular intervals. When the gas readings become stable (+/- 10-20% of the mean reading), the measurement is complete. The emissions rate is then determined by using:

$$v = \frac{Q}{A_{FC}}$$

Where, v is velocity (m/s), Q is flow rate ($m^3$/s or L/s), and $A_{FC}$ is the area of the flux chamber ($m^2$).

This is then followed by the other equations at the beginning of this section, to reach $E_{cap}$, which is emissions rate in g/capita/day.

### 2.3. Closed Flux Chamber Principles

The FC is lowered into the containment (pit/tank) with the gas analysers attached, the vent pipe removed, and the hole it leaves behind closed (airtight with a bung/lid etc.). GHG concentration data is measured at regular 10-minute intervals. This method relies on using the headspace volume and concentration/time to determine the emissions rate. As this method does not require the flow rate to be measured, it is ideal for when flow rate values are low.

All gas concentration (%) measurements were converted to parts per million (ppm) concentration (by multiplying by 1000), and then to $mg/m^3$ using the following formula:

$$C_{mg/m3} = \frac{\left(\frac{C_{ppm}}{10^6}\right) \times MW \times 1000}{RT/P}$$

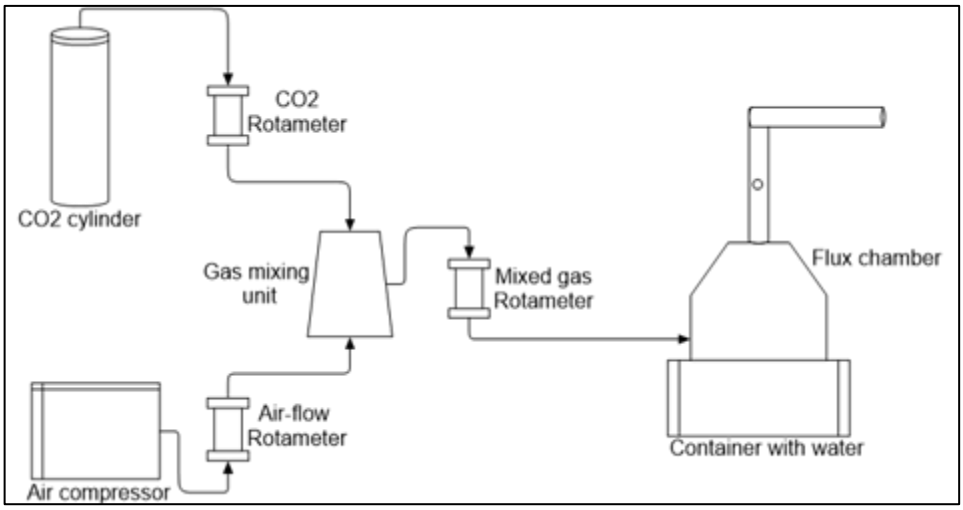


*Figure 3: Calibration set-up for closed FC*

Where, $C_{ppm}$ is the concentration of gas in ppm, *MW* is the molecular weight of the gas under consideration (g/mol), *R* is the ideal gas constant (0.000082057 atm·m3 /mol·K), *T* is the absolute temperature (K), *P* is the absolute pressure of the gas (atm), and $C_{mg/m3}$ is the concentration of gas in $mg/m^3$.

A linear plot between $CO_2$ ($mg/m^3$) and time (min) can be made, which can then be evaluated using the line of best fit. The gradient of this line (m) can then be used to continue to calculate the emissions rate.

The gas concentration values (in $mg/m^3$) from each measurement event are then plotted as a function of time. The slope m, in units of $mg/m^3$ ·min derived from a linear fit of the data is then used to compute the flux using the following equation:

$$E_{cap} = \frac{m \times 1440 \times 10^3 \times V_{FC} \times A_{con.}}{A_{FC}} \times N$$

Where, $E_{cap}$ is the emission rate per capita (g/cap/day), *m* is the gradient of the linear regression, 1440 is minutes in a day (min/ day), $V_{FC}$ is the volume of the FC ($m^3$), $A_{con.}$ is the surface area of the containment ($m^2$), $A_{FC}$ is the surface area of the FC ($m^2$), and *N* is the number of people in the household.

## 3. Results & Discussion

### 3.1. Laboratory Calibration

***Rotameter*.** The initial rotameter calibration tests compared density-based conversions to manual rotameter conversions (*figure 4*). The difference between the converted Qi and measured Qi generally increased with increasing flowrates, but the difference was larger for the manual method, which also had differing trends across the four countries. Using density conversion calculations gives more accurate results for calibration compared to practical rotameter calibration. This is likely since the flowrate is calculated using the volume that was displaced, and is therefore subject to human measurement error, especially as the flowrates increase. In future work, it is suggested that density-based conversion is used to determine rotameter calibrations, when the gas used is not the same as what the rotameter is originally calibrated for. Practically, this allows for the further calibration of the FC to be carried out immediately, without requiring the purchasing of an additional rotameter, adding costs and time.

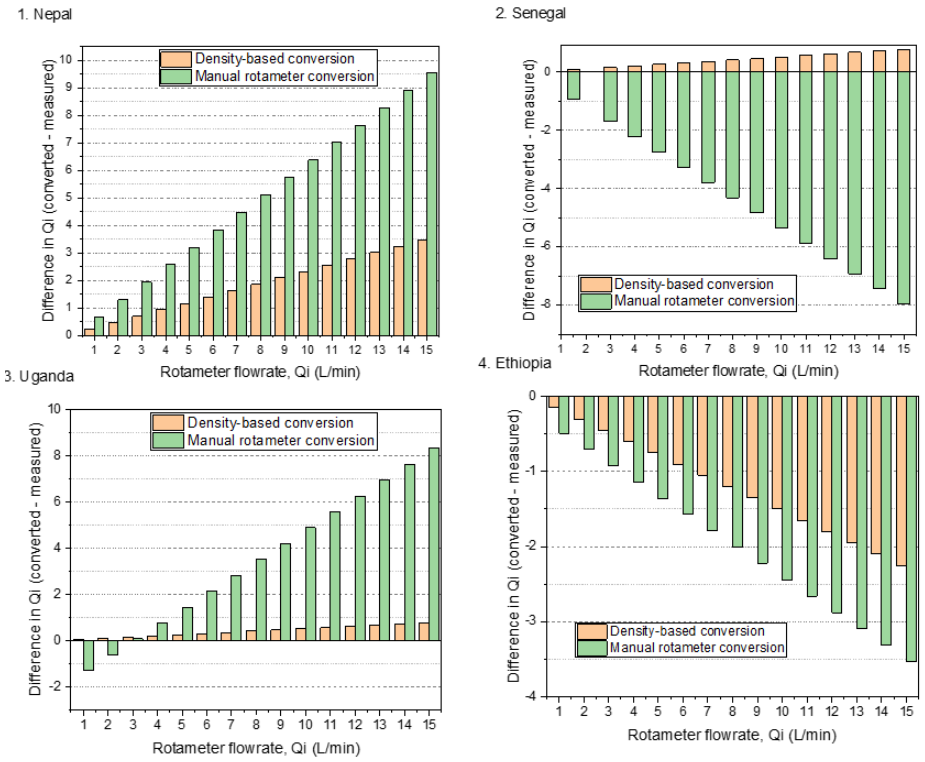


*Figure 4: Rotameter calibration comparison of manual displacement vs density-based conversion in each country.*

***FC Calibration.*** The outlet flowrate, Qo, was compared with the density converted Qi using the Piecewise Linear Regression model (PWL). PWL regression was used because the data showed clear segments in all cases. From the graph (*figure 5*) it is possible to determine the most appropriate times to use this method when in the field. For example, the data for Nepal suggests that this method can be expected to gather reliable results, using a 6" chamber, before the elbow, when the measured flowrate is over 5 l/min. Not only does this data give the minimum detectable flowrate, but also identifies, when appropriate, where the conversion factor should be changed when reaching higher flow rates. This can be seen clearly in the data from Senegal, where at around 10 l/min both measurements before and after the elbow experience a change in gradient. The data also suggests that it is less accurate when working at the higher and lower ends of the spectrum. Although the data across the countries follows a similar trend, due to the different materials used in making the FC, it is essential to carry out this calibration. These results show that all the FC constructions can produce valid results, but that it is necessary to conduct this calibration before undergoing work in the field.

Calibration was conducted both before and after the L-shaped elbow joint on the ventilation pipe. This joint was designed as an optional extra to use when taking measurements in awkward spaces. It is important to note that the use of the elbow joint slightly reduces the ability of the FC system to monitor lower Qo values, increasing the lowest value to ~6 l/min instead of ~5 l/min.

### 3.2. Open Chamber Pilot Test

The data recorded here is often very low to zero across the board, suggesting that the flowrate of the emissions produced is too low to be picked up by the anemometers and FC (lower than the ~5 l/min that is reliably measured throughout FC calibration). It has been suggested that by using a vent pipe to overcome issues such as pressure build up, they tend to create larger problems instead (Conen and Smith, 1998). Other researchers have posed that different results can be expected depending on whether the FC is operating at low or high airflow rates, with those at the lower end giving underestimated results (Gao and Yates, 1998).

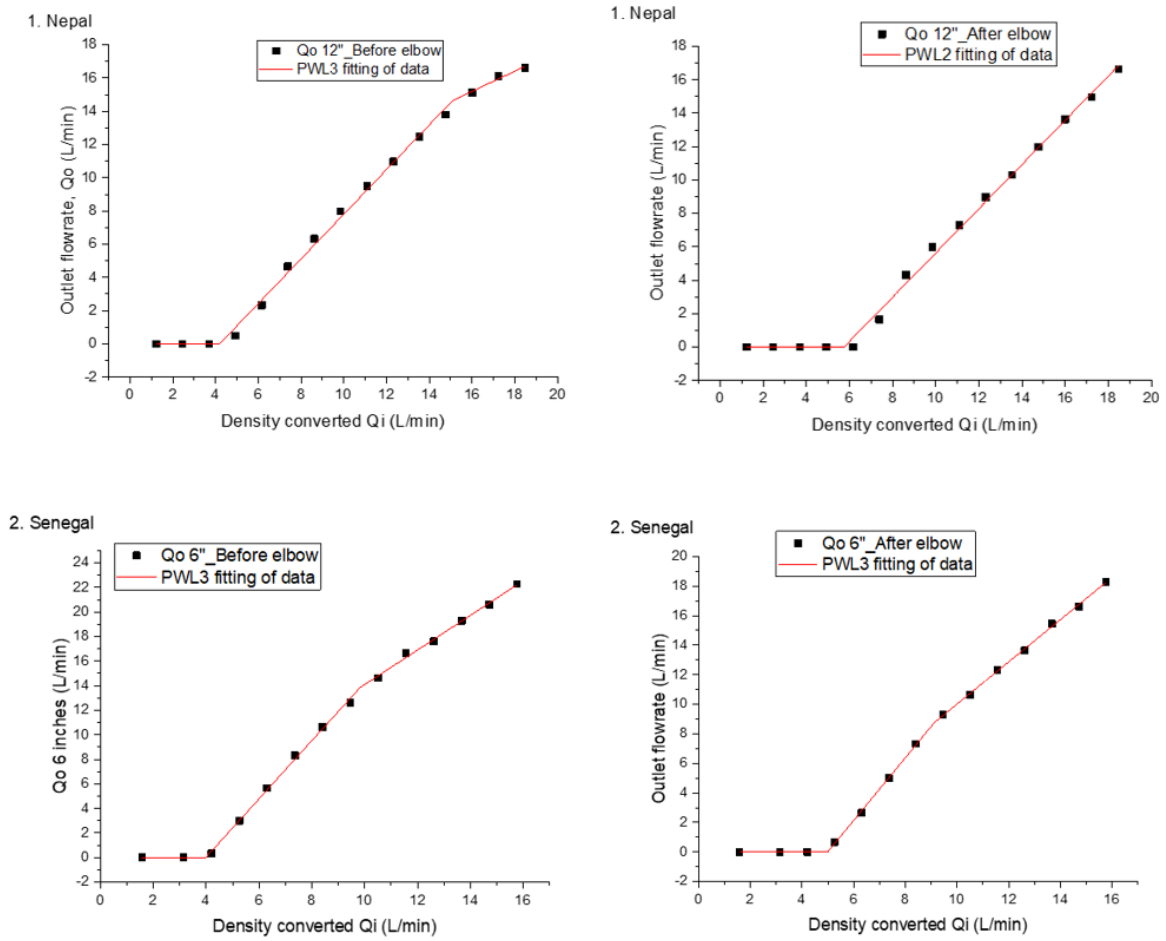


*Figure 5: How density was used with PWL2/3 data to get the best results*

For the current field conditions experienced, it would be best to use a FC with a wider diameter and smaller height, with a narrower vent pipe attached. This would allow for a greater number of emissions to enter the FC, with the same headspace, while increasing the output flowrate measured. In turn, this would allow the open chamber to be used at lower flow rates. However, as the diameter of the FC is limited due to the size of pit latrine openings, the height needs to be large enough to acquire a sufficient volume of gas. Therefore, this can lead to issues in recording low-value flow rates, even when a vent pipe with a narrow diameter is used. Taking this into consideration, the open chamber method is suggested to be used when the diameter of the FC can be increased to more than 12", or when the inlet flowrate is above ~5 l/min (depending on the calibration).

### 3.3. Methodology Considerations

Current methodologies are not uniformly designed and have limitations, such as not working on both septic tanks and pit latrines (i.e., on a liquid /solid surface) (WERF 2010). Designing a FC that would work for both these situations and was designed purposely for use on onsite sanitation, was integral to the design of this FC. Much of the adapted designs of FC are coupled with the power backup to run a fan that mixes gases, leading to a complex, weighty design, which is harder to replicate by other researchers (Diaz-Valbuena *et al.* 2011; Truhlar *et al.* 2016; Somlai, Knappe, and Gill 2019; Huynh *et al.* 2021). Removing bulk out of the FC design, increasing usability, and reducing the cost of associated necessary equipment was key to this design and methodology – all of which is achieved by repurposing the GA5000 and G200 landfill gas analysers. Additionally, here the method does not require taking gas samples and analysing them in a laboratory. This allows greater potential to not only reach remote areas which are often overlooked due to geographical location, the associated logistics and costs, but to also

increase the number of sites that are sampled. The limitation here is the battery life of the devices, but this can be improved by carrying a spare, fully charged backup for longer days.

### 3.4. Data Considerations

In addition to the measurement method itself, supporting information needs to be collected on the containment status. This should include, when it was last emptied, the dimensions, if possible, number of household users, how much sludge and liquid is present at the time of measurement recording (using simple stratification methods), where the inlets and outlets are in relation to the measuring site, etc. Where possible, if laboratories and researchers have the resources, samples can be taken from the containments to be characterised/analysed using methods described by Strande, L. and Brdjanovic, D. eds., (2014). The use of the multiparameter probe is important to include as it provides details for parameters that have an impact on the overall emissions produced. ORP is especially useful in pits/tanks which are flooded, where the profile make-up cannot be determined. This data is important to collect to determine how households empty their containments, whether this is by emptying floodwater when it rains or cleaning out the bottom sludge too.

Management of sanitation systems can also have an impact on the total amount of greenhouse gases the system produces, with regular emptying and composting suggested as methods of GHG reduction (Mills *et al.*, 2020). Moreover, gaining an understanding of other items put into the containments, whether this be other household waste, toilet tissue or water from anal cleansing, can all provide information that contributes to the total GHG emissions profile. Pardo *et al.*, (2015) state that by adding or substituting certain bulking agents you can reduce the $N_2O$ emissions by 53% and $CH_4$ emissions by 71%. If this can be better understood, actions can be taken to reduce GHG emissions from onsite sanitation.

## 4. Conclusions

In general, purely theoretical estimates of GHG emissions from onsite sanitation seem to often overestimated values (WERF, 2010) when compared to field measurements. For example, the IPCC figure for $CH_4$ at 25.5 gram/capita/day compared to 10.7 gram/capita/day and 11 gram/capita/day made by Diaz *et al.* (2011) and Truhlar *et al.* (2016), respectively. Even though there exist some variations in the actual GHG emissions reported, based on existing literature, including both theoretical estimates and direct field measurements, it is evident that the GHG from onsite sanitation are not negligible (Cheng *et al.*, 2022).

This paper has highlighted two low-cost methods to measure GHG emissions from onsite sanitation systems, depending on the equipment available and features of the containment being measured. The methods used are purely field-based and require no extra laboratory work to obtain GHG emissions data. They offer the researcher the opportunity to conduct further characterisation of the system if they have access to the facilities to do so but does not rely on this type of sample collection to generate emissions data. The methodology detailed in this paper measures the representative gas measurements rather than the instantaneous measurements by gas sampling and analysis (such as those by Diaz-Valbuena *et al.*, (2010) and Huynh *et al.*, (2021)). These methods aim to provide a base for further study and development into empirical data collection on GHG emissions from onsite sanitation systems, especially in LMICs.

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