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Measurement approaches for greenhouse gas emissions from rice II: advanced technology for accelerating throughput

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The systematic acquisition of field data is a major bottleneck for identifying scalable solutions that effectively reduce emissions while maintaining productivity in agricultural systems such as rice. This 2nd volume of a multilayered presentation of Greenhouse Gas (GHG) emission measurements in rice fields links up with a review of scientific findings achieved with well-established measurement approaches. Special emphasis is given to advanced systems with laser-based trace gas analyzers (TGA) integrated into an upgraded closed chamber system. A synchronized field experiment was conducted under Alternate Wetting and Drying (AWD) and Continuous Flooding (CF), comparing a) manual sampling with gas chromatography representing a time-tested reference method, b) a TGA in a stand-alone (portable) configuration, and c) a TGA assembled with a semi-automated multi-valve system. Following a preparatory test resulting in an optimum sampling interval of 4 min, the reliability of the TGA measurements was assessed by calculating R^2 from linear regression of gas concentration versus sampling time. Based on a paired t-test, the three approaches did not present any significant difference except for rare outliers with $p \leq 0.01$ reaching a maximum difference of 12.62 mg m^{-2} d^{-1}. In total, these disparities were small compared to overall emission levels and occurred randomly across treatments, indicating that there was no systematic bias between approaches. In the second part of this volume, we broadened the perspective to a comparative assessment of methods supplemented by projecting future developments in GHG measurements in rice. Both portable and multi-valve TGA systems provide greater efficiency and real-time data acquisition while their mutual comparison is a function of research objectives and project settings. Regarding technical features of future measurement systems in rice, we highlighted the multi-valve TGA system as a feasible core component of a high-throughput screening platform intended to identify low-emission rice varieties for immediate dissemination across scales and integration into breeding programs. Finally, we assessed the possible synergies of these high-frequency TGA data sets with other emerging technologies, namely Remote Sensing and Machine Learning, under a diversified regulatory framework for GHG accounting that will likely dissolve the distinction of Tier 2 and 3 approaches for rice production.

KEYWORDS

methane, nitrous oxide, closed chamber technique, manual sampling, gas chromatography, laser-based trace gas analyzers, semi-automated measurements, high-throughput screening

1 Introduction

As the global demand for rice increases, there is a critical need for scalable solutions that can effectively reduce emissions while maintaining productivity. Current mitigation strategies—such as alternate wetting and drying (AWD) and optimized fertilizer regimes—show promise, but their efficacy is highly variable across diverse geographies and practices. Recent syntheses and meta-analyses indicate that AWD can reduce methane emissions by 30-60% without yield penalties, though the magnitude of reduction showed a broad range of variation in individual studies (Yagi et al., 2020; Qian et al., 2023; Ma et al., 2024). Likewise, the impact of fertilizers on GHG emissions has systematically been reviewed in meta-analyses. According to Linquist et al. (2012), the overall fertilizer-induced emission factor for all inorganic N sources was only 0.22% whereas individual fertilizer management options led to significant reductions of N_2O, CH_4 or both."

To provide a comprehensive picture on the measurement approaches for GHG emissions from rice, we compiled a 2-Volume presentation that follows an overall narrative with a clear distinction between.

- a retrospective assessment of well-established approaches with ample publication records (Volume 1 titled "Measurement Approaches for Greenhouse Gas Emissions from Rice I: Technical Evolution and Scientific Results Obtained with Different Methods" by Vo et al., 2026) and.
- a technical description of emerging technologies related to field measurements and their potential to redefine the state-of-the-art measurement approaches for GHG accounting in the future (this Vol. 2).

At the core of the technical innovations considered in this volume are laser-based Trace Gas Analyzers (TGA). Irrespective of the improved analytics, this approach also requires the deployment of closed chambers, but the response time of these "fast-box" measurements is much shorter (Venterea and Baker, 2008; Pavelka et al., 2018). Higher accuracy in GHG detection can be exploited for enhancing the closed chamber methodology to evolve into scalable solutions in rice production. Laser-based analyzers were previously used in GHG measurements, such as the same instrument as used in our study (optical feedback cavity-enhanced absorption spectroscopy) of Licor[1] (Gachibu Wangari et al., 2023; Daelman et al., 2024), dual quantum cascade laser analyzer (Gütlein et al., 2017), and off-axis integrated cavity output spectroscopy analyzer (Piatka et al., 2024). These emerging technologies provide high-precision, real-time gas concentration data, potentially overcoming some of the limitations of traditional methods such as manual sampling in combination with gas chromatograph (GC) and Eddy Covariance (see Volume 1).

To test the reliability of the laser-based TGA for the specific requirements of GHG measurements in rice fields, we conducted a synchronized field experiment under AWD and Continuous Flooding (CF) in the Philippines. In this field experiment, we compared the TGA in different field configurations to manual sampling with a GC, representing a time-tested reference method. A preparatory test was conducted to assess the minimum sampling interval required to achieve a near-linear slope that accurately projects the slope over a longer time frame, i.e. a 30-min placement of the chambers. Based on this experiment, we opted for 4-min chamber placements in our field experiment as a conservative figure to have sufficient time to discard the initial and final records of a placement interval. At the same time, this preparatory test was also used to optimize the technical configurations of the field design, such as the maximum length of tubes for gas sampling among others. To our knowledge, this is the first field study to directly compare portable and multi-valve configurations of a laser-based TGA for measuring CH_4 fluxes from rice paddies relative to a conventional GC reference. Earlier studies employing laser-based analyzers in rice systems (e.g., Simpson et al., 1995; Rajasekar and Selvi, 2022; Bonilla-Cordova et al., 2024; Kajiura and Tokida, 2024) generally used single configurations or prototype setups, without comparative evaluation relative to other analytical methods.

The objectives of this field study were (1) to evaluate the accuracy and performance of portable and multi-valve TGA systems against the GC method, and (2) to assess their potential

1 https://www.licor.com/products/soil-flux/LI-7810

as a foundation for high-throughput GHG (HTG) screening. The findings also demonstrate how such a platform could support standardized, scalable evaluations within a Tier 2 carbon-accounting framework. In addition, the resulting high-resolution datasets provide a basis for future integration with data-driven analytical approaches, including machine-learning (ML) tools, to enhance data interpretation and upscaling.

Although the fast-box set-up can be applied for assessing all types of crop management practices, the findings of our study have specific relevance for future research to identify low-emitting rice varieties. Based on previous experiences in improving rice production systems, introducing improved rice varieties was a successful modernization strategy, resulting in a faster and wider adoption by farmers as compared to recommended changes in Natural Resource Management (Yamano et al., 2016). Given the strong interaction of plant traits with GHG emissions, the identification of low-carbon rice varieties is a promising approach with the perspective of breeding new varieties with desirable plant traits. Building on this foundation, the present study evaluates field-based measurement methods capable of detecting genotype-specific differences in CH_4 fluxes under realistic cultivation conditions. However, the systematic assessment of low-carbon rice varieties will require the testing of a large number of rice plants that exceed the capacity of the conventional measurement set-ups.

The final section of this volume moves from the level of a field study to a broader perspective on the applicability of laser-based TGA for measuring GHG fluxes from rice paddies and its prospects for a variety of different GHG accounting contexts. Rather than detailing instrument engineering aspects, it emphasizes comparative performance, operational efficiency, and project-level applications, ensuring relevance to agronomic and environmental researchers as well as practitioners involved in GHG monitoring. In this comparative assessment, we applied a set of criteria to determine the strengths and limitations of each approach for the specific requirements of GHG measurements in rice fields – either as stand-alone approach or in combination with other emerging technologies such as Remote Sensing and ML.

In the next step, we then set these strengths and limitations in the context of developing an HTG. Based on the technical features of the different approaches, we discussed the functionality of an HTG for low-carbon rice varieties. Such a screening platform could be instrumental in accelerating the rapid, standardized, and scalable evaluation of the potential of rice varieties for mitigation purposes. For rounding up this multi-layered presentation of field measurement approaches, this 2nd volume ends with an assessment their future role under a diversified Tier 2 framework by considering the development of market-based and non-market carbon accounting in rice production.

2 Materials and methods

As outlined in the introduction, this Volume 2 consists of a field study conducted in rice fields which is then used as the foundation for a broader perspective on future developments of GHG measurement approaches. As for the latter, this outward-looking assessment is rather generic by combining the experimental findings with citations of relevant literature, so that this section on Materials and Methods only specifies the implementation and data evaluation of the field study.

2.1 Different measurement approaches

Volume 2 of our comprehensive study focuses on an advanced laser-based technique that embodies distinct operational trade-offs in accuracy, mobility, and scalability. In our field study, we included manual sampling method in combination with GC analysis for benchmarking these findings with a time-tested and commonly used reference method.

2.1.1 Manual sampling followed by GC analysis

The manual sampling approach (MSC) is schematically shown in Figure 1 for a setup with six chambers measured synchronically. The samples were immediately transferred into pre-evacuated in the present study of 30 mL glass vials fitted with butyl-rubber septa and stored at ambient temperature until analysis. The number of chambers that can be sampled in this set-up is mainly limited by the availability of field staff. The recommended deployment time of the chamber is 20–30 min, with sampling intervals typically at 0, 10, 20, and 30 min after chamber closure (Sander and Wassmann, 2014), as schematically shown by 24 vials in Figure 1A. The length of the observation period represents a compromise between (i) ensuring a detectable concentration gradient in the headspace over time and (ii) limiting the temporary exposure of plants to adverse conditions, such as high temperature and low CO_2 concentration. The GC for detecting CH_4 concentrations from rice fields is typically equipped with a flame ionization detector (FID). All samples were transported within a distance of 1 km after the sampling procedure and analyzed within the following day using an SRI GC-8610C. This GC/FID unit was operated at a column temperature of 70°C and a detector temperature of 330°C. The column was 3 m long and packed with Porapak Q (50–80 mesh) while the carrier gas was N_2.

2.1.2 Direct sampling with laser-based analyzer/ portable TGA

As an alternative to manual sampling with syringes, the chamber headspace air can be directly connected to a laser-based TGA (e.g., LI7810, LI-COR Inc., Lincoln, Nebraska, USA) equipped with a built-in pump for continuous concentration records. Figure 1B illustrates the field setup for TGA measurements in the stand-alone (portable) configuration. The TGA is equipped with a battery that allows field operations for several hours. The laser type is optical feedback cavity-enhanced absorption spectroscopy. The raw data of the TGA consists of one concentration record per second, which is internally stored. The TGA does not require any calibration as per the supplier's information.

In the present field experiment evaluation, the TGA was sequentially connected to six chambers for a 4-min interval using

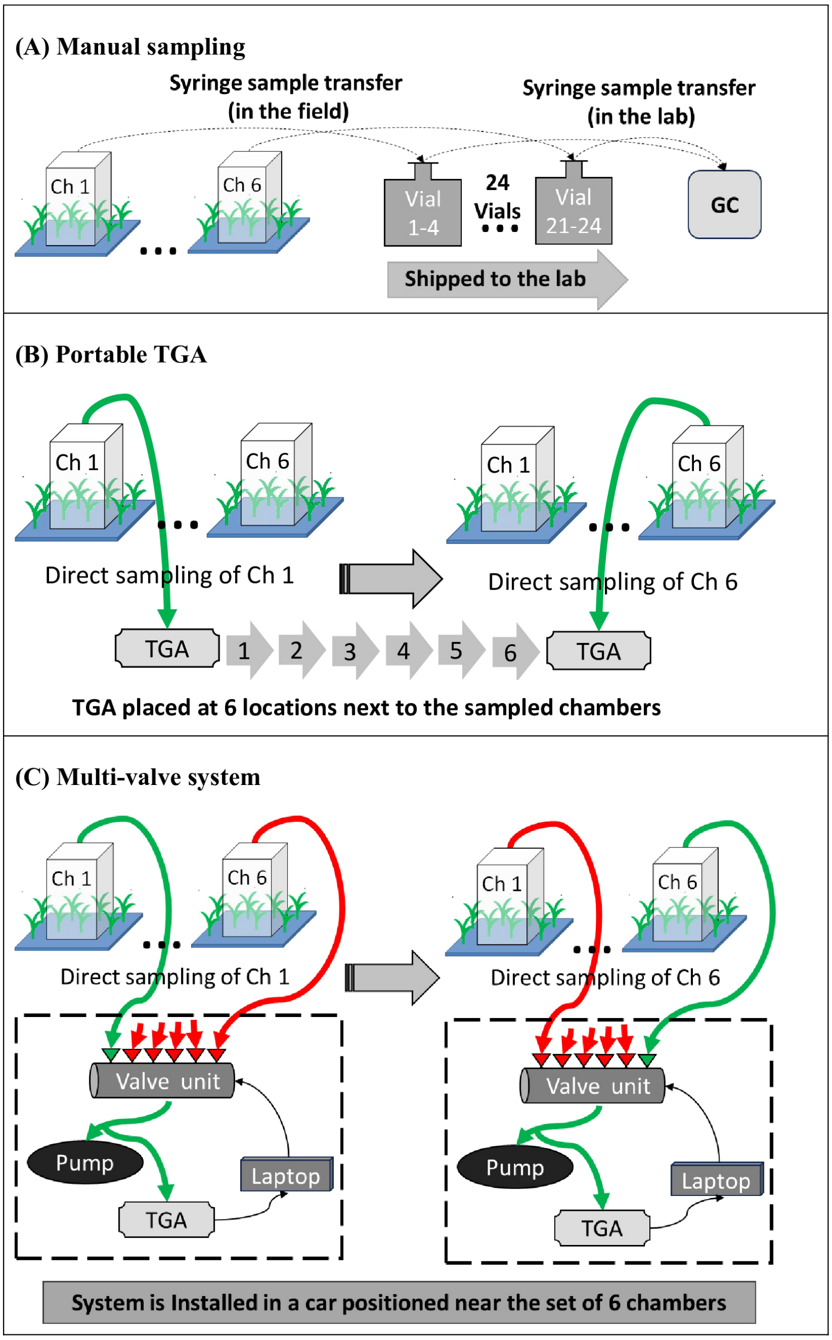

FIGURE 1
(A–C) Schematic presentation of sample transfer and configurations of the analytical instruments for a field setup with six chambers; dotted arrows indicate sample transfer through syringes while solid arrows indicate direct sample transfer through tube connections in an active state (green) and an inactive state (red); likewise, the multi-valve unit is displayed with open (green) and closed (red) valves for sampling of the respective chamber.

a Teflon tube of about 6.5 m in length and an outer diameter of $^1/_8$ inches. After completing the 4-min interval for a given chamber, the operator moved to the next chamber's location, where another chamber was placed and connected to the portable TGA (Figure 2B). This move and the necessary detachment and connection of the tube lasted for 1–3 min, resulting in more or less evenly distributed sampling intervals over the measurement cycle. Because of the frequent detachment from the chamber connection and the subsequent exposure to ambient air, the portable system can be operated without a moisture trap, which seems an advisable technical add-on for the continuous operation of an automated system (see below).

This sampling interval of 4 min was derived from a preparatory test with chamber closure durations of up to 30 min. The results of this experiment are tabulated below (Table 1) while graphical illustrations are provided in Supplementary Materials. The test

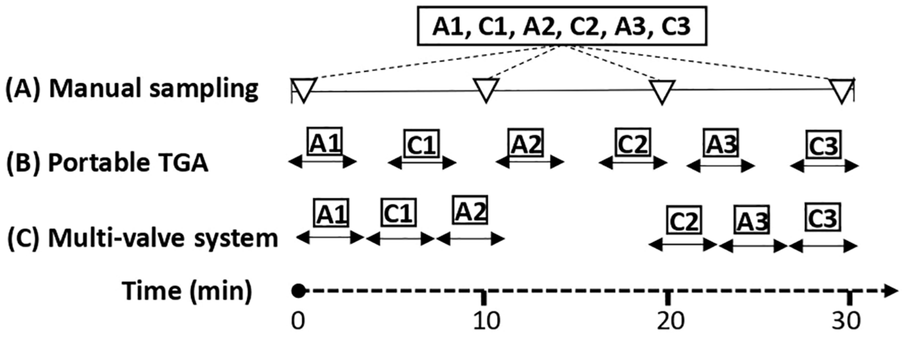

FIGURE 2
Schematic presentation of sampling intervals over one measurement cycle with six chambers illustrating the difference between **(A)** synchronous sampling indicated as triangles and **(B, C)** sequential sampling indicated as double-arrowed lines; A1,2,3 = chambers of the plots AWD1,2,3, respectively; C1,2,3 = chambers of the plots CF1,2,3, respectively. See explanations in the text.

showed that concentration gradients stabilized after approximately 1 min, reflecting initial flow-rate adjustment. Based on regression diagnostics (see Table 1), a 4-min interval was selected to balance between signal stability, measurement accuracy, and sampling throughput. The standard calculation window (61–210 sec) excluded the initial flow adjustment phase and last phase of each run to avoid any potential synchronization disturbance.

2.1.3 Direct sampling with laser-based analyzer/multi-valve system

The integration of the TGA into a multi-valve system (see photos in Supplementary Figure S2) facilitates testing wider range of different crop management practices (water management, varieties, etc.) which is a typical task of agronomic field experiments. This semi-automatic sampling system (Figure 1C) was designed to increase the number of plots that can be covered under given time and labor constraints. The multi-valve system is operated from a car that was stationed as near as possible to the plots (Figure 2C). The design of the multi-valve system is similar to the field measurements described for a flux study conducted in the Congo Basin using a fully automated sampling system (Daelman et al., 2024). The added components comprise (i) a set of solenoid valves assembled in a compact unit to direct the air from a given chamber into the TGA, (ii) a laptop equipped with a software toolkit to configure I/O modules as well as a customized software for operational control, (iii) two sets of batteries (12 V) to power the

TABLE 1 Slopes of concentration increase across different time windows in the preparatory test.

Observation	Effective time window (sec)	Total sampling interval (sec)	Slope (ppb/sec)	R^2	P-value
Observation 1	a) 61-120	150	6.229	0.999	5.06E-90
(2,000-14,000 ppb)	b) 61-150	180	6.178	1.000	1.20E-146
	c) 61-180	210	6.128	1.000	5.25E-209
	d) 61-210	240	6.113	1.000	8.32E-277
	e) 61-1800	1830	6.167	1.000	0
Observation 2	a) 61-120	150	4.184	0.999	1.12E-85
(2,000-10,000 ppb)	b) 61-150	180	4.19	1.000	1.84E-145
	c) 61-180	210	4.187	1.000	1.15E-204
	d) 61-210	240	4.184	1.000	1.41E-269
	e) 61-1800	1830	4.106	1.000	0
Observation 3	a) 61-120	150	2.889	1.000	1.44E-108
(2,000-8,000 ppb)	b) 61-150	180	2.872	1.000	3.00E-180
	c) 61-180	210	2.863	1.000	2.28E-256
	d) 61-210	240	2.902	0.999	7.31E-237
	e) 61-1800	1830	2.808	1.000	0

The coefficient of determination (R^2) and p-values are reported for each measurement interval to indicate the linearity and statistical significance of the slopes.

entire system, as well as (iv) an additional pump. This additional pump was needed to increase the airflow in the tube connection to allow sampling with longer tube lengths that would have exceeded the capacity of the pump built into the TGA.

The system is connected to the six chambers through Teflon tubes with a maximum length of 60 m and a $^{1}/_{8}$-inch outer diameter. Each tube was connected to one solenoid valve assembled within a valve-unit controlled by customized software to facilitate sample transfer to the TGA. We also added a moisture trap consisting of a membrane filter as a protective device to prevent potential moisture interference with the analyzer under humid field conditions. In contrast to the portable TGA, the multi-valve system allows an immediate switch from one chamber to another once the predetermined sampling time has passed. As we wanted to maintain some degree of synchronicity among both TGA approaches, however, we interrupted the measurements of the multi-valve system after three chambers and phased the sampling of the remaining chambers to achieve a reasonable fit among chambers of either approach (Figure 2).

2.2 Comparative field study

We conducted field measurements with all three approaches to record emissions using identical chambers and – as much as possible – synchronized measurement periods. The rice fields are located on the IRRI experimental farm (14°09′45″ N, 121°15′35″ E). Six plots (12 m × 12 m; 144 m²) were planted with the variety IRR11N313/IRRI 244 at a seeding rate of 30 kg ha^{-1}. Each chamber enclosed an average of 18 plant hills. The two water managements, AWD and CF, were represented by three replicate plots each. Fertilizers were applied at rates (per ha) of 130 kg N, 50 kg P_2O_5, 30 kg K_2O, and 5 kg Zn. The field measurements were implemented during the wet season 2024 on two different dates (on 11 and 18 August 2024) at two consecutive weeks labeled as W1 and W2 in the results. These dates corresponded to 51 and 58 days after seeding, respectively, with two observation time windows (08:00 and 10:00) per day. The weather condition on the measurement dates was characterized by mean temperatures 28–29°C, high relative humidity (~84%), strong solar radiation, calm winds (< 0.5 m s^{-1}), and no rainfall. A total of 24 data points were obtained per measurement approach, encompassing 2 water managements × 2 dates × 2 time windows × 3 replicates.

2.3 Data evaluation and analyses

2.3.1 Calculation of emission rates

The closed static chamber technique is based on the assumption that a given emission from the soil – either through the soil, water, or plant surface – causes a concentration increase in the respective GHG in the chamber headspace. The concentration of gas within the closed chamber is then a function of (i) the amount of gas emitted, (ii) the period of the chamber enclosure, (iii) the volume of the chamber headspace, and (iv) the temperature. Given a rectangular or cylindrical shape, the chamber volume is directly related to the chamber height, as the area covered along the chamber height does not change.

Closed chamber measurements require the calculation of the slope in the concentration as the initial step for estimating emission rates. Assuming a steady emission over time, the emission rate (mg CH_4 m^{-2} h^{-1}) can be calculated from the linear slope of the accumulation of gas in the chamber derived from the ideal gas law (Minamikawa et al., 2015).

$$Flux_{CH4} = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \rho \times \frac{273}{273 + T}$$

where:

$\frac{\Delta C}{\Delta t}$ is the concentration change over time (ppm CH_4/min).

V is chamber volume (m^3).

A is chamber area (m^2).

ρ is gas density (0.717 kg m^{-3} for CH_4 at 0°C), which allows conversion from ppb (volume-based) to mass units.

T is the mean air temperature inside the chamber (°C).

In this formula, the CH_4 concentration is expressed in ppm (= 10^{-6}), which compensates for the conversion from kg to mg (= 10^6) via the gas density (kg m^{-3}). However, in our TGA measurements, we initially calculate the slope as ppb CH_4/sec (Figures 3, 4), which has to be converted to ppm/min for an input into this formula as follows:

$$\frac{\Delta C}{\Delta t} = 0.06 \times slope$$

2.3.2 Approaches for slope detection

The assessment of manual sampling data followed standard procedures outlined in numerous publications (e.g., Minamikawa et al., 2015). In contrast, the analysis of TGA-based measurements required a =customized approach for slope detection following automated key steps in slope calculation, quality control, and data processing.

These steps are implemented through R script that comprises the following sequence:

1. Cycle definition: The measurement process consisted of sequential sampling from six chambers. Each chamber is measured for 4 min, forming one complete cycle (Figures 2B, C).
2. Data preprocessing: Each 4-min interval (240 sec) undergoes preprocessing to minimize artifacts from valve switching and tube connections. The first 60 sec and the last 30 sec of each interval were systematically discarded to remove potential disturbances caused by manual or automatic switching (Step 2, Figures 3A, B). The remaining 150 sec interval (from 60 to 210 sec) was then defined as a “standard time window” for slope calculation.
3. Slope calculation: The CH_4 flux is determined by applying linear regression to CH_4 concentration data over the standard time window. The script extracts the slope and the coefficient of determination (R^2) of the linear regression

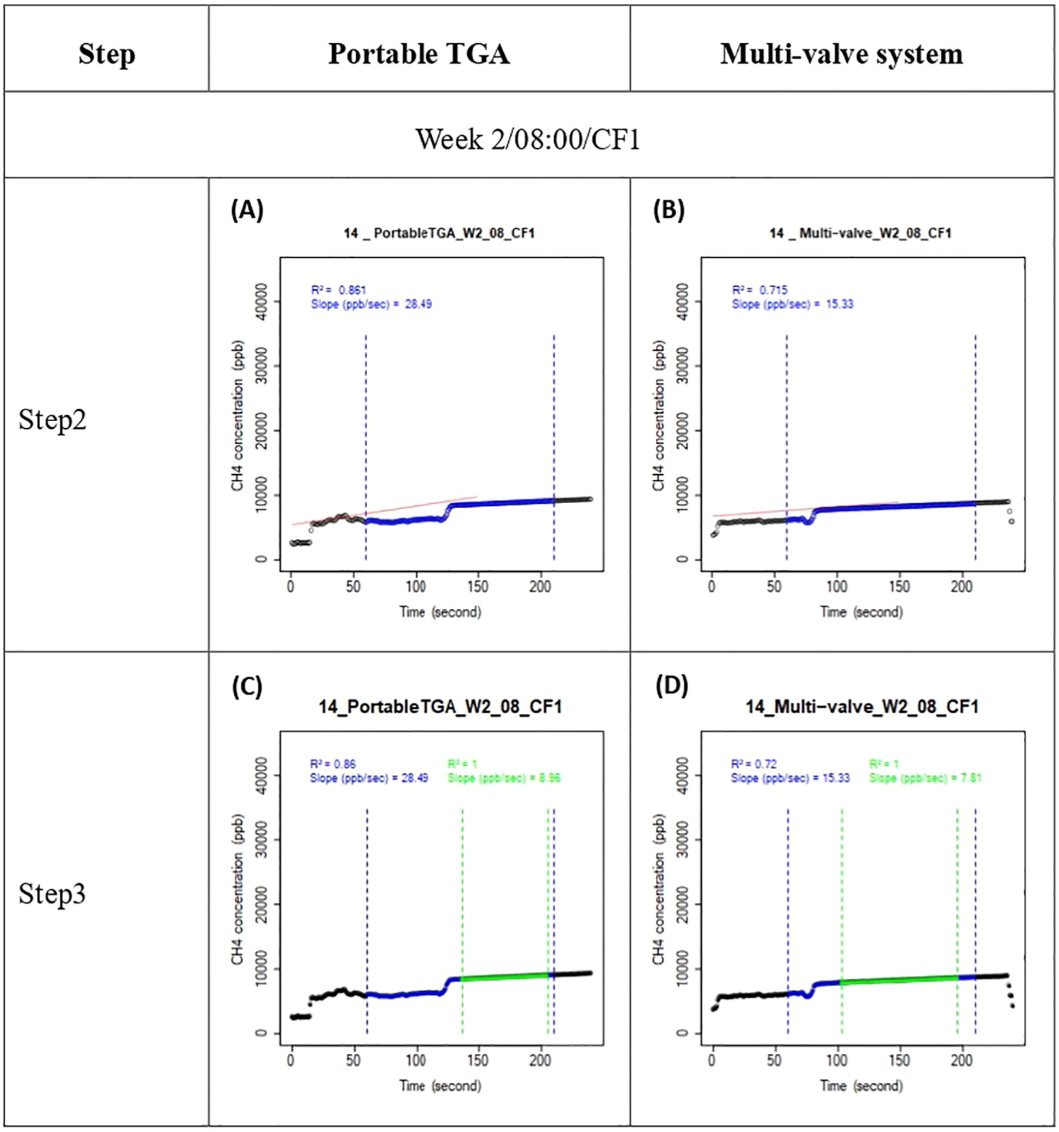

FIGURE 3
Examples of raw data processing for TGA measurements. **(A, B)** Step 2: data preprocessing defining the "standard time window" (60–210 s); low-quality regression fits (R^2 < 0.9) are marked in blue. **(C, D)** Step 3: zooming into the standard time window to identify a more stable "adjusted time window" (green). Slope diagrams are labeled using the internal convention: 1–24 = tracking numbers; W1/W2 = Week 1/Week 2; 08:00/10:00 = measurement time; AWD/CF1–3 = alternate wetting and drying/continuous flooding replicates.

of emission. A threshold of $R^2 \geq 0.90$ was adopted following Minamikawa et al. (2015) and other chamber-based studies to ensure data reliability and comparability with the MSC results. Although there is no fundamental scientific rationale of setting $R^2 = 0.90$ as the threshold, this value has evolved over the years as a widely used benchmark for acceptable regressions.

4. Manual inspection: Given the R^2 value of the standard time window is ≥0.9, the slope is adopted for the respective measurement to calculate an emission rate. If the R^2 value falls below 0.9, a manual inspection is performed to identify a more stable segment of data that exhibits strong linearity (Step 3, Figures 3C, D). As for the programming, R packages (ggplot2, dplyr, lubridate, and stringr) are employed to plot time-series data, visualize, and refine slope calculations to ensure accurate CH_4 flux determination. The "locator()" function is used interactively in the R environment to select a stable segment of data by specifying start and end points on the plot. Each manually selected segment covered at least 60 s of continuous data to ensure robust slope estimation. This allowed us to visually inspect the data and select the appropriate interval for slope calculation. Once the irregular or inconsistent sections of

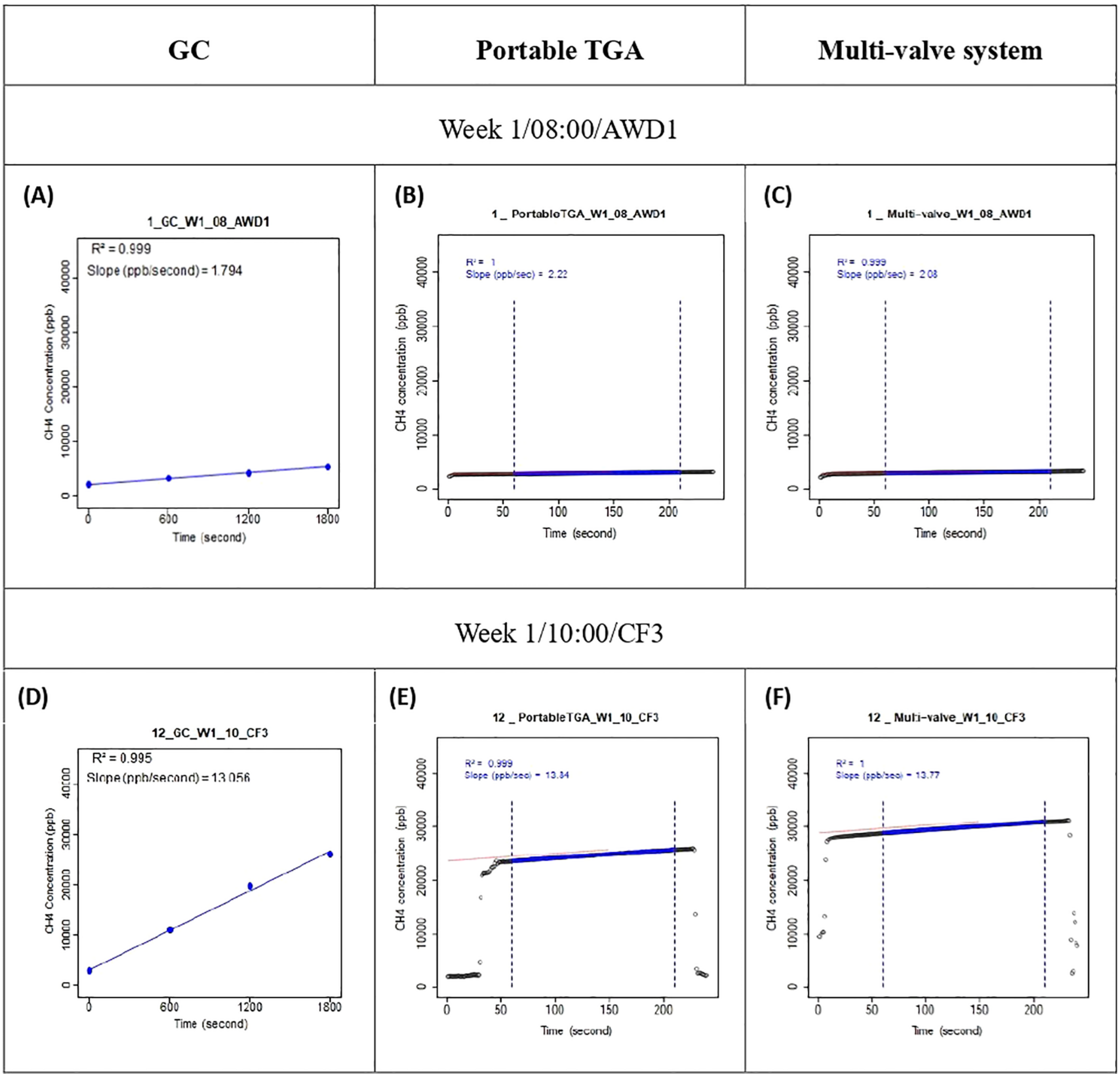

FIGURE 4
Selected examples of raw data leading to an immediate calculation with R^2 > 0.9. **(A, D)** Slopes generated from GC data. **(B, C, E, F)** TGA plots show the entire 4-min interval with the standard time window (60–210 s) indicated by dashed vertical blue lines. Data within this window are also highlighted in blue. Slope diagrams are labeled using the internal convention: 1–24 = tracking numbers; W1/W2 = Week 1/Week 2; 08:00/10:00 = measurement time; AWD/CF1–3 = alternate wetting and drying/continuous flooding replicates.

the standard time window are discarded, the recalculated R^2 values for these "adjusted time windows" are indicated by dashed vertical green lines (see examples in Figure 3). The data segment within this adjusted time window is then highlighted in green, with improved linearity as the basis for the slope calculation and further analysis.

5. Bias minimization: Manual inspections were required for approximately 5% of all TGA measurements in this study, corresponding to 7 out of 72 records (~9.7%) with R^2 < 0.9. To minimize observer bias, all manual selections were guided by standardized diagnostic outputs, uniform criteria for window length (≥ 60 s), and recalculated statistical diagnostics. Examples of both standard and adjusted regressions are shown in Figure 3.

3 Results

3.1 Preparatory test to determine the sampling interval

Table 1 shows the results of a preparatory test to determine the appropriate measurement interval. Supplementary Figure S1 is shown alongside as a graphical presentation of the concentration gradients. The preparatory test comprises of three observations conducted using closed chamber placed in a rice field over a 30-min period. The observations recorded different slopes in the concentration gradients ranging from 2.808 (observation 3) to 6.167 (observation 1) and resulting in different concentration ranges inside the chambers placed in the rice field. In each observation the concentration gradient became stable after about 1 minute, which can be attributed to fluctuations in the flow rates immediately after switching of the valves before the laminar flow reached a steady state. In turn, the initial minute of each sampling was discarded from the calculation of the slope used for subsequent comparative field analyses. To evaluate the effect of different measurement intervals, four shorter time windows (a–d) were compared with the full 30-minute dataset (window e) as shown in Table 1. The coefficient of determination (R^2) was used to assess the linearity of the regression model, and p-values to test the statistical significance of the slopes. While all shorter windows (a–c) showed good agreement with the full-duration gradient, window d (61–210 s) was selected to apply for the field experiment. During the actual field measurements, the valve was switched after 240 seconds, and the standard evaluation window was set from 61 to 210 seconds. This excluded both the initial 60 seconds (to avoid instability effects) and the final 30 seconds (to minimize potential data distortion due to minor asynchronies between system control and real-time recording).

3.2 Linear regression of gas concentration evaluation

The linear regression of gas concentration recorded by the three approaches was evaluated using the R^2 of the linear regression between the time window of recording and the CH_4 concentration. A total of 72 records were obtained from the 24 comparative measured data points for the test. The bulk of these linear regressions (90.3%) resulted in an R^2 value greater than 0.9 (Figure 4). Notably, all samples collected manually met the R^2 >0.9 threshold within the standard time window of recording of 30 min with four data points sampled. An equally high proportion of the TGA measurements (90%) also showed a satisfactory R^2 >0,9. The 10% of the records (7/72) that showed lower R^2 values (ranging from 0.22 to 0.86) were attributed to 4.2% (3/72) from the portable TGA measurement approach and 5.6% (4/72) from the multi-valve system within the 4 min of time window of monitoring each.

3.3 Comparative analyses of the flux rates

Flux estimates obtained were comparable among the different approaches throughout the 24 comparisons (Figure 5). These charts underline the high degree of agreement between the results among the different approaches obtained in parallel measurements as well as their capacity for the distinction between AWD and CF in terms of GHG emissions rates. The differences among approaches were higher under continuously flooded plots, where background emission rates were higher, and fluctuations in CH_4 emissions were more pronounced. Despite some occasional discrepancies, all three approaches reliably captured comparable emission trends under varying soil moisture conditions (Figure 5).The mean daily emission rates among the plots monitored were 38.42 ± 21.56, 35.57 ± 22.07 and 32.55 ± 20.73 mg CH_4 m^{-2} d^{-1} for the GC, portable TGA, and multivalve approach under AWD, respectively, and 107.26 ± 24.83, 101.23 ± 21.70 and 94.63 ± 27.72 mg CH_4 m^{-2} d^{-1} under CF (Table 2A). The two-way ANOVA test (Table 2B)

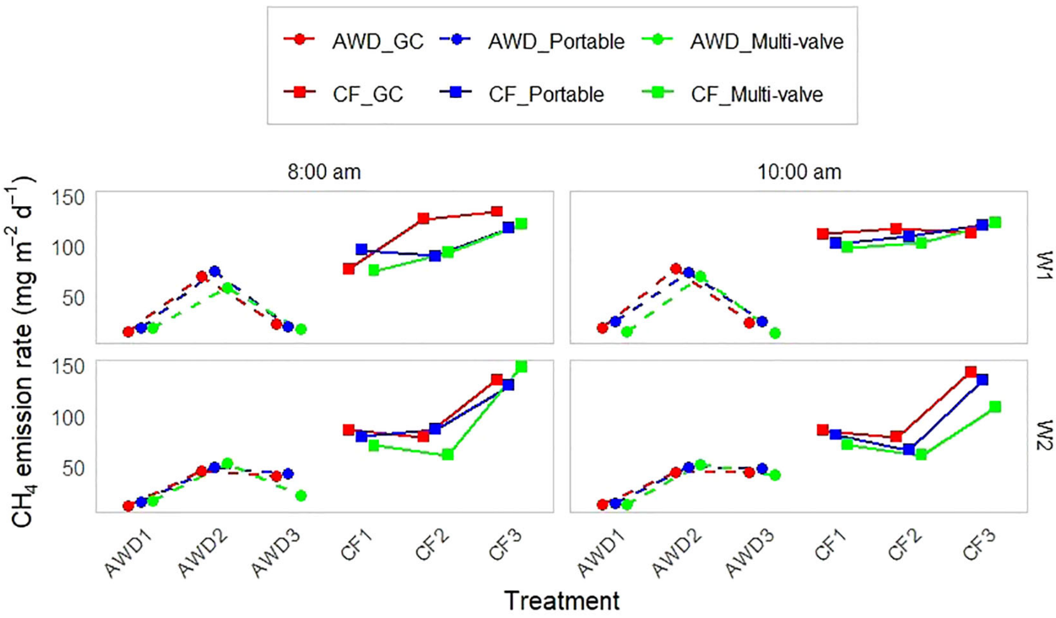

FIGURE 5
Comparisons of the emission rates obtained with three measurement approaches for AWD and CF replicates in Week 1 (W1) and Week 2 (W2) at 08:00 and 10:00.

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TABLE 2 (A) Descriptive statistics and (B) two-way ANOVA for daily emission rates across treatments and approaches.

A) Descriptive statistics					
Treatment	Approach	Mean (mg CH^4 m^{-2} d^{-1})	SD (mg CH^4 m^{-2} d^{-1})	CV (%)	n
AWD	GC	35.57	22.07	62.05	12
AWD	Multi-valve	32.55	20.73	63.69	12
AWD	Portable	38.42	21.56	56.12	12
CF	GC	107.26	24.83	23.15	12
CF	Multi-valve	94.63	27.72	29.29	12
CF	Portable	101.23	21.7	21.44	12
B) Two-way ANOVA					
Factor	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Treatment	1	77290.01	77290.01	143.25	0
Approach	2	820.01	410.01	0.76	0.47
Treatment:approach	2	343.52	171.76	0.32	0.73

SD, standard deviation; CV, coefficient of variance; Df, degrees of freedom; Sum Sq, sum of squares; Mean Sq, mean of squares; F-value, variance between groups/variance within groups; Pr(>F), probability that the F-statistic is greater than the observed value under the null hypothesis.

demonstrated no interaction between treatment and approach ($p = 0.728$), which indicates the consistency of the results across the measurement approaches used.

Composite comparisons for all treatments and approaches were conducted through a paired t-test (Table 3). The applied significance levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$ serve to evaluate the strength of agreement between methods. Although a few comparisons showed statistical significance at the $p < 0.05$ level (see Table 3: #1, #3, and #5), only one reached the $p < 0.01$ threshold (Table 3: #1) and none met the most stringent criterion of $p < 0.001$. These results suggest that, although some differences exist between certain method pairs, they are generally weak to moderate statistical strength. The absence of consistently strong significant differences ($p < 0.001$) further supports the conclusion that all three approaches produce consistent and closely aligned CH_4 emission estimates. Despite minor variability, the results demonstrate a high level of agreement among the three measurement approaches.

To further evaluate the agreement among the three measurement approaches, Bland–Altman analyses were conducted for each method pair under AWD and CF water management conditions (Figure 6). Under AWD, the analyses revealed minimal mean bias and narrow limits of agreement, indicating that GC, Portable TGA, and Multivalve measurements are largely interchangeable at the individual measurement level. Under CF, biases were higher and limits of agreement wider, reflecting greater inherent variability in CH_4 fluxes associated with continuously flooded conditions rather than methodological inconsistency. These findings complement the two-way ANOVA and paired t-test results, which demonstrated no significant interaction between treatment and measurement approach and only occasional minor differences among methods. Collectively, the statistical and Bland–Altman analyses provide robust evidence that the three approaches yield consistent and comparable CH_4 emission estimates across different water management regimes.

TABLE 3 Paired *t*-test results comparing CH_4 emission rates among measurement approaches (GC, portable, and multi-valve) under AWD and CF conditions.

Comparison ID	Group	Comparison	Mean Diff	p-value	CI lower	CI upper	Sig_0.05	Sig_0.01	Sig_0.001
#1	AWD	GC vs portable	-2.83	0.01	-4.78	-0.88	Yes	Yes	No
#2	AWD	GC vs multi-valve	3.03	0.21	-2.02	8.08	No	No	No
#3	AWD	Portable vs multi-valve	5.86	0.03	0.83	10.88	Yes	No	No
#4	CF	GC vs portable	6.03	0.16	-2.67	14.74	No	No	No
#5	CF	GC vs multi-valve	12.62	0.01	3.53	21.71	Yes	No	No
#6	CF	Portable vs multi-valve	6.59	0.11	-1.77	14.95	No	No	No

Mean Diff, mean difference; CI ,95% confidence interval; Sig, significance thresholds of $p < 0.05$, $p < 0.01$, and $p < 0.001$.

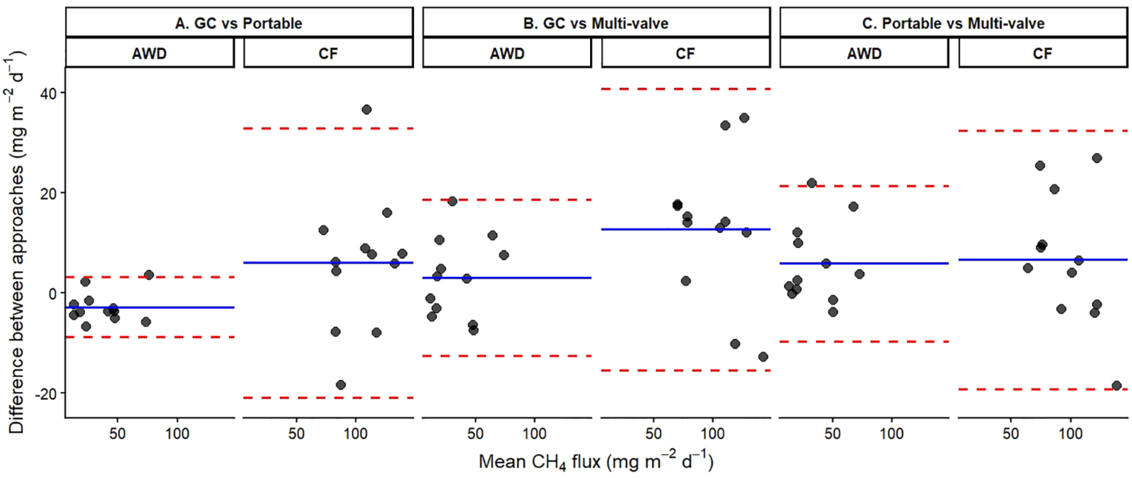


FIGURE 6
Bland–Altman plots of CH_4 flux among three measurement approaches. **(A–C)**: **(A)** GC vs Portable, **(B)** GC vs Multi-valve, **(C)** Portable vs Multi-valve. AWD and CF water treatments are shown as sub-columns. Points = paired measurements; solid blue line = mean difference (bias); dashed red lines = limits of agreement (± 1.96 SD).

4 Discussion

Chamber measurements evolved as the standard approach for GHG emission assessments in rice fields (Livingston and Hutchinson, 1995). Recent developments in sensor technologies can be tapped to enhance data resolution and to enable high-throughput measurements, leading to more refined emission estimates. We can realistically assume that the use of chambers will remain the prevailing approach for field campaigns to assess GHG emission rates within the next decade. We demonstrate in this study that improving field instrumentation through a laser-based analyzer could play an important role in enhancing the reliability of chamber measurements which aligns with other field studies (Cowan et al., 2014; Shao et al., 2022).

It should be noted that the consistently high R^2 values (>0.9) in the manual approach can primarily be attributed to the long sampling intervals (3 × 10 min), in contrast to the portable and multi-valve systems performing continuous measurements at one-second intervals. The latter inherently captures a higher degree of fluctuations in concentration changes over time, which has likely contributed to the lower R^2 values observed in some cases.

The ability of high-frequency measurements to resolve rapid concentration changes is particularly important when capturing dynamic CH_4 emission events such as ebullition. Kajiura and Tokida (2021) demonstrated that advanced optical sensors allowed the detection and quantification of CH_4 ebullition in chamber measurements in rice paddies—emission events that would likely be missed by manual sampling methods. The ability to distinguish sources of emissions such as from ebullition and actual emissions through the plant is expected to increase capacity to differentiate varieties. The need for this type of study illustrates the importance of real-time data capture for accurately characterizing CH_4 emission dynamics, reinforcing the value of continuous laser-based analyzers such as the TGA used in our study.

As for the statistical analysis, our results suggest a moderate to high level of agreement among the manual sampling, portable and multi-valve systems for measuring CH_4 emissions. The limited number of comparisons reaching higher levels of significant differences (especially $p < 0.01$ and $p < 0.001$) indicates that all three systems provide comparable measurement results. Although the different approaches were implemented in the field simultaneously, the sampling intervals still differed slightly because of inherent distinctions among them (Figure 3).

The published guidelines for rice chamber measurements (e.g., Minamikawa et al., 2015) recommend deployment times of up to 30 min for manual sampling, while methodological reviews indicate that artifacts such as temperature rise, CO_2 drawdown, or stomatal responses typically occur only with prolonged closures or inadequate ventilation (Rochette and Eriksen-Hamel, 2008; Heinemeyer and McNamara, 2011; Pavelka et al., 2018; Mazengo et al., 2024). In our setup, the chambers (headspace nearly 200 L) were equipped with a fan and a ventilation tube. We applied short sampling intervals (4 min for TGA; 30 min for manual sampling). We therefore consider it unlikely that these brief, infrequent closures would affect plant growth or final grain yield under the tested field conditions.

Using the manual sampling/GC approach as the reference, our study showed that the TGA system could determine overall CH_4 emission rates in much shorter intervals. The use of the TGA provides the following advantages:

- The TGA enables real-time measurements of GHG concentrations, allowing for immediate visualization of emission dynamics during field measurements. According to the supplier, the response time from the change in concentration from 0 to 2 ppm is ≤2 sec in standard configuration. An experienced operator can immediately identify eventual technical anomalies that might be caused by improper air mixing due to a defect fan inside the chamber headspace or an obstructed airflow in the tubing. This real-time diagnostic capability by observing irregular concentration patterns and pressure changes displayed on the laptop screen enhances data reliability and ensures the integrity of flux measurements. Additionally, data can be instantly downloaded and processed using an optimized R script, thus enabling rapid flux calculations.

- The TGA offers significantly higher accuracy and sensitivity in CH_4 measurements under field conditions than conventional manual sampling methods. Although GC/FID systems have been reported by instrument suppliers with an LOD of 100 ppb, the TGA had a precision of 0.60 ppb with a 1-sec integration time as applied in our measurement setup. In turn, the use of a TGA enables real-time flux estimation and high-frequency measurements with greater efficiency than conventional GC/FID methods.
- The TGA measurement diminishes the time required for individual CH_4 records in field conditions. Assuming a field operation is done by one researcher, the manual sampling approach can cover a set of three chambers maximum within 30 min of deployment time. Additional time is needed to transport samples to the GC lab for chemical analysis of concentration. In contrast, the TGA (both portable and multi-valve) can assess 7–10 plots within the same period, depending on a deployment time of 4 or 3 min per chamber, respectively. Based on these rates and an 8-h working day, one operator can collect samples from approximately 48 plots day^{-1} using manual sampling method (30-min interval) versus more than 110 plots day^{-1} using the multi-valve TGA system with a 4-min interval, demonstrating a clear gain in scalability and efficiency. This increased throughput is achieved through the multi-valve TGA configuration used in this study, which supports up to 12 chambers per measurement cycle managed by solenoid valves for sequential sampling. The portable TGA, while providing equivalent analytical performance and data output, requires the operator to manually relocate the analyzer between chambers. Each relocation, including disconnection and reconnection of tubing, typically lasted 1–3 min (mentioned in Section 2.1.2). Although this step introduces slightly longer operational times than the automated multi-valve system, the portable configuration remains advantageous for smaller or spatially dispersed experimental layouts. Approximate equipment and setup costs for manual GC and TGA configurations are presented in Table 4. Furthermore, the delay in data acquisition is a notable limitation for time-sensitive measurements. On the other hand, the TGA system overcomes this constraint by its ability to immediately deliver concentration data on-site (Fiedler et al., 2022), thus enhancing both measurement efficiency and operational logistics, particularly when a larger number of plots need to be assessed.
- To enhance the possible number of measurements, the computer-controlled multi-valve unit ensures consistent sampling intervals throughout each measurement cycle. The switching of the solenoid valves eliminates the need for moving the chamber to another spot as required in the set-up of a single tube connection. This configuration reduces human intervention, ensures precise sampling intervals, and mitigates disruptions associated with tube handling. The system is particularly advantageous for high-throughput measurements.
- The technical configurations used in our multi-valve system were based on previous experiences with other land use systems (Daelman et al., 2024). It is understood, however, there could be different scenarios of implementing such a field set-up as a function of research objectives and field design. The tubing of the sample transfer is a critical factor as it should be reasonably long to reach numerous plots, but

TABLE 4 Individual assessment of strengths and limitations of all five measurement approaches according to objectives and logistical requirements of field measurements in rice.

Objectives and logistic requirements	a) Manual chambers	Laser-based analyzer	
		b) Portable TGA	c) Multi-valve system
1) Mobility for multi-site comparison	Very high mobility	High mobility with moderately long installation time	High mobility, but relatively long installation time
2) Velocity of screening	Suitable due to parallel measurements, but very labor-intensive	Suitable due to sequential measurements	Very suitable due to parallel measurements
3) Recording of diurnal cycles	Low suitability due to laborious field operations	Low suitability due to laborious field operations	Potentially expandable with semi-automatic chambers
4) Accuracy of detection	Moderate accuracy of GC analysis	Highly accurate sensors working at plot scale	Highly accurate sensors working at plot scale
5) Affordability[2]	Low costs as long as a GC lab is available	Affected by high investment costs for TGA	Affected by high investment costs for TGA and valves
6) Simplicity of operation and data analysis	Very simple as long as a GC lab is operational	Programming skills required	Technical skills in operations and programming skills required

not too long to impede a laminar air flow. The latter could in principle be ensured through larger pumping rates, but those might lead to an under-pressure in the closed chambers. Our choice of the sampling interval (4 min) represents a compromise for achieving a high sampling frequency without impairing the detection of a linear concentration slope. As we have used 6 valves in our set-up, we assume that, based on our experience with routine measurements, 12–16 valves should be assembled in one unit to achieve high efficiencies in field operations.

The operational costs for manual sampling would include the researcher's time for gas collection, the supplies for gas sampling, and the charge for lab analyses. These costs will sum up to a sizable amount per year, given that a single cropping season might require more than 1000 samples [one field experiment for the screening of 20 rice varieties in Vietnam collected nearly 10,000 vials (Vo et al., 2023)]. The existing TGAs, although requiring a higher initial investment, have significantly lower running costs that might compensate for the costs of a GC/FID analysis over a multi-year time horizon. The TGA (particularly the model LI-7810, tested in this study) does not have specified lifespan details; however, its design indicates that it can operate without the need for calibration, as it maintains a maximum drift of <1 ppb per 24 hours. Routine maintenance in our facility includes replacement of the air inlet filter approximately twice per year and regeneration of the purge desiccant upon saturation to sustain performance under humid tropical conditions. These standard procedures, together with periodic verification using calibration gas (the same schedule applied for the GC system), have ensured reliable operation in continuous field use. As TGA use becomes mainstream, we foresee that its cost may be reduced. While now, TGA and GC may have similar investment costs, GC requires further investment in laboratory facilities suitable to host the machine. Beyond the logistical and technical considerations, it is also critical to assess whether different measurement approaches yield comparable results in practice. While previous studies have reported discrepancies between GC-based (Pihlatie et al., 2013) and laser-based approaches, our results demonstrate a high degree of consistency among all three methods tested-GC, portable TGA, and the multi-valve system. Christiansen et al. (2015), for instance, observed significant differences between GC and cavity ring-down spectroscopy (CRDS), particularly for CH_4 measurements under variable field conditions. These differences were largely attributed to the higher sensitivity and continuous data acquisition capabilities of CRDS, which allowed detection of short-term flux pulses that manual sampling may be missed. In contrast, our study found no significant interaction between treatment and measurement approaches and only weak to moderate differences between method pairs in the paired t-tests. Notably, none of the comparisons met the $p < 0.001$ significance threshold. This level of agreement suggests that, under our field conditions, all three approaches produced comparable CH_4 emission estimates. These findings reinforce the suitability of laser-based chamber techniques for emission quantification as well as highlight the advancements in instrumentation and operational practices that may account for the improved methodological alignment compared to earlier studies. Moreover, the capacity of laser-based systems to detect short-term flux peaks, such as ebullition events described by Kajiura and Tokida (2021), may help explain their robust performance across treatments in our study. Nevertheless, we acknowledge that these results are based on a single-season, single-site comparison, and further validation across multiple locations, cropping seasons would be valuable to confirm the robustness and general applicability of the observed agreement among methods. Overall, our findings demonstrate that the modified TGA system is a viable alternative to manual sampling with GC analysis, offering real-time concentration data, operational efficiency, and long-term cost savings. However, the choice between methods should consider factors such as study objectives, resource availability, and infrastructure constraints.

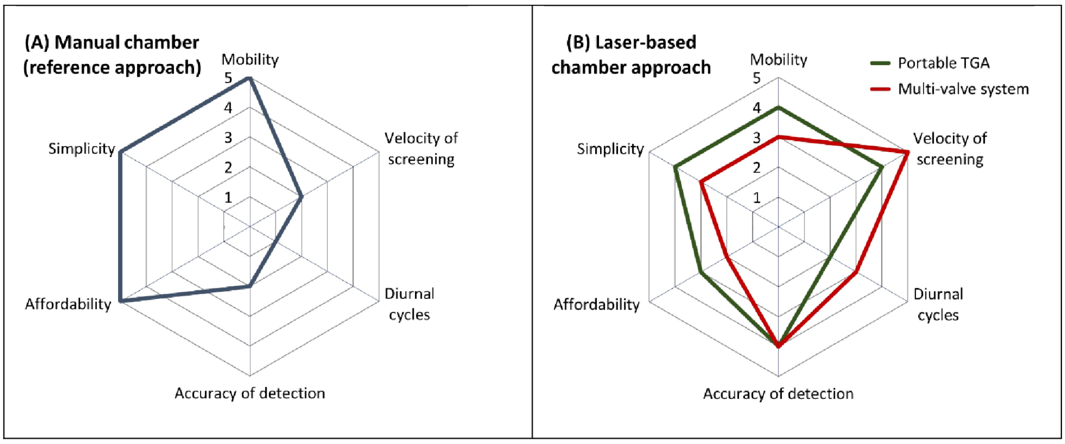
The high-resolution datasets generated from the TGA systems offer valuable opportunities for advanced statistical analytics. As detailed below, Machine-learning (ML) may improve flux prediction, identify emission patterns, and support 3 GHG accounting frameworks. Integrating ML with automated measurement systems represents a logical next step toward comprehensive, data-driven GHG monitoring in rice production.

While the analytical framework of this study can be extended to other GHGs, we focused on CH_4 as the dominant GHG source in flooded rice systems and the primary target for mitigation. The findings presented here therefore pertain mainly to CH_4 and may not directly apply to CO_2 or N_2O, whose flux characteristics differ in response to chamber closure time and temporal variability.

5 Evaluation and future prospects of GHG measurement approaches in rice systems

5.1 Comparative assessment of strengths and limitations of measurement approaches

While the previous section of this 2nd volume focused on discussing the field study, we are now providing a comparative assessment of these advanced systems in supplement to Volume 1 dealing with conventional measurement approaches. In both volumes, however, we used the manual sampling/GC approach as the time-tested reference compared the approaches according to 6 criteria comprising objectives and logistic requirements (Table 4), namely 1) mobility for multi-site comparison, 2) velocity for the screening of treatments or varieties, 3) recording of diurnal cycles, 4) accuracy of detection, 5) affordability and 6) simplicity of operation and data analysis. Based on the individual assessments in Table 4, we scored the approaches for all criteria within a scale ranging from 1 (corresponding to a limitation of the respective approach) to 5 (corresponding to a strength), which is reflected in the radial charts of Figures 7A, B.



Legend:
5 Strength of the approach
4 Moderate strength
3 Balanced performance
2 Moderate limitation
1 Weakness of the approach

FIGURE 7
(A, B) Schematic presentation of strengths and weaknesses of all approaches according to six selection criteria for the specifics of GHG measurements in rice (see Table 4 for individual assessments).

As for the two TGA approaches (Figure 7B), the stand-alone instrument performed better in terms of mobility, affordability and simplicity, whereas the multi-valve system received the highest score for velocity and also a slightly better score for diurnal cycles. The latter was based on the sampling system that already encompasses the principal components of an automated or semi-automated chamber system, which seems like a realistic option for future applications. Regarding the investment costs of manually sampled chambers (Figure 7A), it should be noted, though, that we assumed for the scoring that there is access to a functional GC lab and excluded eventual costs for such infrastructural requirements. The airtight enclosure of the vials ensures that the samples can even be shipped for long distances to the analytical lab including international shipment by air, without compromising data quality (Vo et al., 2023). On the downside of this remote analysis, this procedure might entail considerable lead time until the concentration records become available to the field researchers, thus preventing any swift adjustment in the sampling procedure in response to unexpected results.

As for the inherent uncertainties in the measurement approaches assessed in this study, we do not see principal differences among them. Although very labor-intensive, there is no systematic impediment against manual sampling on a daily basis throughout the season as done by Chu et al. (2015). Given higher efficiency, laser-based instruments could reduce the daily labor inputs – or increase the number of field trials – but it should be noted that the need for day-to-day operations still represents a sizable labor constraint to such an experiment.

However, integrating these new instruments into a fully automated sampling system may unlock their full analytical power. As mentioned above, the automated flux system employed in the Congo Basin (Daelman et al., 2024) represents an example for this technical integration. This system was designed for N_2O fluxes and includes shallow chambers that are not suitable for enclosing entire rice plants. Likewise, the automated GHG analysis designed by Kiese et al. (2018) that used an earlier laser-based analyzer was designed for grassland with chamber closure near the soil surface. Nevertheless, an application of automated chamber systems with an integrated TGA could adopt the sampling design of comparable systems with GC as analytical unit that are presented in Volume 1 (Vo et al., 2026). The comparative advantages of such a laser-based system are (i) lower logistic requirements for operating a field lab, (ii) reducing the enclosure time for the rice plants and thus, the risk of possible interference with plant development and (iii) increasing the possible sampling frequency within a given day or the number of trials tested.

5.2 Prospects for application in high-throughput systems of GHG measurements in rice

The comparative field assessment in this study was conducted in the context of designing the basic feature of a high-throughput system for GHG screening of different factors such as varieties. The term “high-throughput” is widely used in agricultural research in the context of phenotyping (HTP). In a nutshell, HTP is an automated approach that uses advanced technologies, data analytics, and automation to rapidly and accurately collect and analyze a large volume of phenotypic data from plants. These

TABLE 5 Technical features required for an HTG system to screen rice varieties, alongside existing approaches that can be tapped for lessons learned.

Technical feature	Lessons learnt from existing field approaches
1) Analytical capacity	TGA/ multi-valve: Sufficient for ground-based measurements, but not yet for air-borne measurements.
2) Automation	Fully Automated Chamber (FAC): Integrated robotics in other GHG studies can be used as prototypes.
3) Monitoring of plant parameters	HTP: Technology for high-throughput phenotyping can be adopted.
4) Data-driven Analysis.	TGA/ multi-valve: Vast amounts of data require sophisticated database management that should, in the future, incorporate machine learning (ML).
5) Ex-post field validation	MSC + EC: Field validation of the low-carbon varieties can be conducted at multiple sites (MSC) or through continuous records (EC).

features also apply in one way or the other for a future system of rapid and scalable GHG measurements, although the technical transformation from the existing approaches into a functional high-throughput system for detecting GHG fluxes (HTG) poses specific challenges (Table 5). It should be noted though, that we broadened the scope of approaches considered for HTG beyond this Volume 2 and included the two technologies elaborated on in Volume 1, namely Fully Automated Chamber System and Eddy Covariance:

The complex technical requirements are listed in Table 5 alongside the existing approaches that can be used to derive some lessons learnt for their technical transformation into an HTG system:

- The available Analytical Capacity (#1) of the TGA is characterized by high accuracy and in the case of the multi-valve system, also sufficiently short measurement intervals for the screening of varieties. While the basic analytical requirements for a ground-based screening platform are met, the airborne measurements will need further improvements to comply with the needed accuracies.
- Likewise, the features of automation (#2) appear very challenging. Robotics could play a crucial role in minimizing labor requirements, but the technical implementation of a genuinely high-throughput system will still require considerable effort. As an example for a prototype, Kiese et al. (2018) designed a system using a robotics to move the static chambers on rails. The rubber-sealed chamber is placed on top of a metal collar on the soil surface for a closure time of 15 min. Although this system was optimized for continuously gathering GHG data from a small number of lysimeters embedded in the soil, these construction principles allow various options of modifications and extensions to be scaled for a fully automated setup to test a large number of rice treatments or cultivars.
- The intended monitoring of plant parameters (#3) could benefit from the ample experience in applying HTP systems. This analogy could be very instrumental in considering the complex G×E×M interactions in plant development to select better-performing rice varieties with low emission potentials.
- As for the data-driven analysis (#4) of a future HTG system, the existing practices of the TGA/multi-valve system (see R-script in Supplementary Materials) present a good starting point but will have to be improved in width and depth for dealing with a large amount of field data and applying innovative approaches such as machine learning.
- Finally, we also listed ex-post field validation (#5) as the basis for an impact assessment and for planning the dissemination of low-carbon varieties. Depending on the scope of such dissemination programs, the available approaches can be tailored for providing data at multiple sites (through MSC) or continuous records (through Eddy Covariance).

The demand for a HTP screening tool is given by previous research that has reported potential genotypic differences in CH_4 flux among rice varieties under comparable management conditions (Zheng et al., 2014; Vo et al., 2023). More recent work provides deeper genetic and physiological evidence for these differences. Roy et al. (2025) demonstrated genetic variation in root porosity, root diameter, and aerenchyma formation-traits crucial for determining CH_4 flux—and showed that these traits are controlled by distinct genetic loci whose haplotypes can guide screening of current elite breeding pools. Jin et al. (2025) identified biochemical traits that influence the composition of root exudates and thereby alter the microbial substrate supply that drives methanogenesis. Together, these findings support the development of low-CH_4 rice through combined physiological and molecular screening approaches.

In the broader picture of agronomic innovations, the future HTG system can be integrated into genomics-based plant breeding, such as the Genome-Wide Association Study (GWAS). While GWAS identifies candidate genes and markers associated with a specific trait, the minimum number of rice varieties used in such studies can vary. For instance, a study mapping the candidate genes for low-nitrogen tolerance in rice seedlings used 295 rice varieties in a GWAS (Li et al., 2022). As for emissions, the published studies encompass field screening of about 20 different rice varieties in parallel (Vo et al., 2023; Hu et al., 2023). Although this number is still an order of magnitude below what is typically considered necessary for GWAS, the use of robotics might drastically enhance the throughput capability of the chamber system.

2 Investment costs low: <10,000 USD; high: 30 - 50,000 USD; very high: > 50,000 USD

5.3 Remote sensing technologies in support of GHG measurements

The emerging feasibility of direct measurements of GHG emissions using satellite-based sensors that might – at least in theory – make any kind of field measurements obsolete. However, there are still orders of magnitude between the precision for GHG measurement needed for rice fields and the technical capabilities of the available sensors. According to Jacob et al. (2022), current imagers for remotely sensing methane sources have detection thresholds in the range of 100–10000 kg CH_4 h-1. While this precision suffices for monitoring high-emitting point sources such as pipeline leaks, it is contrasted by the low magnitude of emissions from dispersed CH_4 sources like rice fields. Derived from the default value provided in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Ogle et al., 2019) as a reference (i.e. 1.3 kg CH_4 h^{-1} d^{-1} for Southeast Asia), the background emission rate of rice fields is about 0.05 kg CH_4 ha^{-1} h^{-1}, requiring an even higher precision to detect flux rates. Even though a direct comparison of these detection limits of point vs area sources would require more detailed calculations of a theoretically detectable area of homogenous rice fields, the gap in sensitivity covering at least 4 orders of magnitude is indicative that it is not possible to use the current satellite-based sensors as a stand-alone approach for relevant research on GHG emissions in rice production.

Another approach for air-borne sensors would be the use of drones, Unmanned Aerial Vehicles (UAVs). Given the short distances between the drone and the field, it can be assumed that the next generation of sensors will be capable of detecting GHG concentrations in high resolution. However, the conversion from concentration values to emission rates still requires a profound description of the 3D-wind field to consider the turbulence over the rice field. On the other hand, properly equipped drones are well-suited for monitoring environmental proxy parameters, e.g. vegetation index (Song et al., 2024) or thermal maps (Velez et al., 2024). However, these drone-based approaches for direct detection of GHG emissions are still experimental and still inherently rely on ground-truthing of GHG fluxes.

Instead of making field measurements obsolete, these innovative technologies will require large amounts of data for ground-truthing and learning steps that can only come from field measurements. Along these lines, some pioneering studies that merge satellite sensors and FLUXNET ground observations based on Eddy Covariance measurements were already initiated (e.g. Jang et al., 2024). Such networking and data-sharing initiatives of the EC community could be considered an instrumental blueprint for future efforts on improving GHG extrapolations. Given the inherent need for large datasets on a range of different ground-truthing sites, the fast-box measurements enabled by laser-based instruments appear as a logical fit for these types of research projects.

In contrast to the Eddy Covariance approach working at field scale, the replacement of the analytical instruments does not alter the fundamental chamber principle. Given the results from our field study, the new measurements obtained with laser-based analyzers are fully compatible with the vast amount of data compiled with the manual sampling approach and could expand the existing database through systematically addressing data gaps in space and time. Even under evolving technology development, each of the five measurement approaches presented in Volume 1 and 2 of this study will have its specific pros and cons within a given application context, namely scientific studies, policy-driven GHG inventories, and or commercial carbon projects among others.

5.4 Assessing the future of field measurements under a diversified Tier 2 framework

Despite ongoing efforts to move from Tier 1 and 2 to Tier 3 approaches in national GHG inventories and carbon crediting projects, it can be expected that many stakeholders involved in these activities will be reluctant to abandon the lower Tiers approaches in the foreseeable future due to their familiarity with the required procedures. It should be noted that the IPCC approach was developed for emission estimates at the national scale with the assumption that emission factors will somehow level off across the different rice growing environments of a given country. By the same token, Tier 2 was conceived by the IPCC with field measurements (to determine national emission factors) at its core, in contrast to Tier 1, which can be applied without measurements.

For individual projects, however, the use of nationally determined emission factors may entail considerable uncertainty due to site-specific factors. McGlynn et al. (2022) argue that Tier 2 factors, while more refined than Tier 1, still introduce systematic bias when applied to project-level carbon accounting in agriculture. As national-level averages fail to capture local heterogeneity in soil, climate, and management practices at project scale, their conclusion for a coherent Tier 2 application is the site-specific data collection for credible carbon crediting. Irrespective of these concerns, the prevailing methodologies of the compliance and voluntary markets[3][4][5] allow for accounting procedures without determining emission factors through field measurements. Given the stipulation of field measurements as the defining feature of the original IPCC Tier 2 concept, the simple adoption of nationally determined emission factors at project scale without empirical evidence from the field is more aligned with Tier 1 than with Tier 2, even though the emission factors may originate from a national Tier 2 assessment.

3 https://cdm.unfccc.int/UserManagement/FileStorage/5IP163JN4RKG2D0XOQZS9T7W8MEYAC

4 https://globalgoals.goldstandard.org/437-luf-agr-methane-emission-reduction-awm-practice-in-rice/

5 https://verra.org/methodologies/improved-management-in-rice-production-systems/

A similar concern can be applied to the relative impact of crop management practices driving GHG emissions as expressed in the IPCC scaling factors. These calculations are based on global defaults embedded in the IPCC formulas that were developed for the 2006 Guidelines compiled about 20 years ago, when the available field studies were very few. The only exception with a more substantiated empirical basis is the procedure for calculating water management impacts, which has been thoroughly revised through updated scaling factors in the 2019 IPCC Refinement. While the scaling factor of the baseline water management (CF) equals 1 by definition, the other options are limited to single and multiple drainage. The latter category seems inadequately broad given the diverse patterns that are technically possible and that were shown to affect GHG emissions in different pathways (Qian et al., 2023). Likewise, the IPCC formula on organic amendments defined rather broad options on the quality and timing of this wide-ranging category. Moreover, the formula and the scaling factors of this calculation procedure were adopted without revision in the 2019 refinements despite a very weak empirical basis when it was developed in the early 2000s. Thus, it seems questionable to what extent the quantifications without *in-situ* measurement will provide a reliable picture of this important driver, e.g. under different rice straw treatments and timings of soil incorporation.

As for N_2O emissions, the available field studies have largely increased over recent decades (Qian et al., 2023), leading to a distinction of two emission factors, namely 0.3% of applied N for CF 0.5% for rice fields with at least one drainage period (Ogle et al., 2019). These new emission factors were then adopted in the incumbent carbon methodologies for rice that require a correction of the CO_2e accounted for the shift from CF to single or multiple drainage. On the other hand, the reduction in N-fertilizer rates and its corresponding reduction in N_2O emissions can at present not be used for generating carbon credits. Though not explicitly stated in these methodologies, this exclusion for carbon accounting can be attributed to uncertainties in the N_2O emissions factors that largely exceed the range of what is tolerated in the general guidelines of carbon accounting standards[6].

Given the emerging ML/AI technologies, the role of *in-situ* measurements will certainly change, but we would argue that their significance will not diminish in the near future. Although these new technologies are generally seen as an integral part of Tier 3[7], they are also instrumental for gap-filling and extrapolations under a Tier 2 framework. Extending this underlying concept to its logical conclusion, the application of ML and AI with site-specific measurements could be used to generate emission models with high site-specificity that may ultimately blur the distinction between Tier 2 and Tier 3 methodologies as defined in the IPCC Guidelines.

6 https://globalgoals.goldstandard.org/203-ar-luf-activity-requirements/

7 https://verra.org/methodologies/improved-management-in-rice-production-systems/

6 Conclusions

In recent years, GHG emissions from rice paddies have gained attention due to their significant contribution to CH_4 budgets and their role in climate change. This study compared standard and advanced measurement approaches to provide evidence-based insights for researchers and practitioners. Despite small discrepancies with the MSC approach used as reference, the TGA systems captured comparable emission trends under varying soil moisture conditions, underscoring their reliability and suitability for application in similar studies and diverse environmental assessments.

The findings highlight that advanced techniques offer improvements in efficiency, precision, and accessibility that can make a difference especially for emerging actors in carbon markets and mitigation initiatives. The advantages of this system include real-time data availability, improved operational efficiency, and decreased long-term costs. Overall, this level of consistency is encouraging, particularly in large-scale or multi-site studies where practical constraints might necessitate the use of different systems.

Furthermore, our study underscores the need for standardized protocols to ensure data comparability across different measurement techniques. As new stakeholders enter the field of CH_4 emission monitoring, selecting an appropriate method will depend on factors such as accuracy, resource availability, and intended application. Future research should focus on refining low-cost, high-accuracy alternatives to enhance accessibility, particularly in regions with limited laboratory infrastructure. By bridging the gap between traditional and emerging measurement methods, this study contributes to the broader goal of improving CH_4 monitoring in rice systems, supporting both scientific progress and policy development for climate change mitigation. In addition to the description of the field measurements, our study addressed the options for semi-automatic data evaluation to enhance efficiency and minimize the need for manual data control. This prototype script can either be adopted or further adjusted in future field measurements of GHG emissions from rice fields and possibly other crops.

This article represents the second volume of a companion study on GHG measurement approaches in rice. While Volume I provided a systematic evaluation of conventional techniques, the present work demonstrates the added value of advanced, laser-based approaches with an emphasis on scalability and high-throughput applications. Taken together, the two volumes deliver a comprehensive framework that links traditional methods used as benchmarks with innovative technologies, thereby equipping researchers, policymakers, and practitioners with complementary tools to advance climate change mitigation in rice systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

TBTV: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. RW: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. RRR: Data curation, Investigation, Methodology, Writing – review & editing. CARC: Investigation, Writing – review & editing. MLCM: Investigation, Writing – review & editing. GW: Methodology, Writing – review & editing. RK: Methodology, Writing – review & editing. AMR: Funding acquisition, Software, Supervision, Writing – review & editing.

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Conflict of interest

The authors declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY FIGURE S1
Illustration of the concentration radiance obtained from the preparatory test.

SUPPLEMENTARY FIGURE S2
Photographic of the 3 measurement approaches used in this study: **(A)** manual sampling + GC analysis, **(B)** portable TGA setup, and **(C)** multi-valve TGA system: while the valve unit consist of 12 solenoid valves, only 6 of them were used in our field experiment due to logistical reason for ensuring synchronous sampling with the other systems.

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