Plant traits influencing greenhouse gas emission potential and assessment of technical options for emission screening with large number of rice varieties

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Abstract

Methane (CH_4) is a major greenhouse gas (GHG), which accounts for 16% of the global GHG effect. In the agriculture sector, rice cultivation substantially contributes 10% of all anthropogenic CH_4 emissions, thus the importance of determining the variables that influence and/or control CH_4 production in rice fields.

Over the last decades, various studies reported differences in the emission potential of CH_4 of different rice cultivars. However, physiological plant traits responsible for such differences are still unknown. A literature review was therefore conducted to collect relevant studies, which examined the differences in CH_4 emission potential of different rice cultivars.

While GHG emission studies from rice are typically done through ‘closed chamber’ measurements, the assessment and sampling of CH_4 emissions from large numbers of rice cultivars (>100) pose a challenge in terms of management of sampling and experimental design.

Therefore, this study has developed recommendations for screening a large number of rice varieties to identify cultivars with low CH_4 emission potential. A new concept and two practical approaches are presented.

Keywords

Methane emission; greenhouse gases; rice; varieties

About the authors

Sebastian Weller, an agricultural biologist, is a post-doctoral fellow at the Universidad Nacional de Cordoba, Argentina, and consultant at the International Rice Research Institute during the conduct of this research study. Dr. Weller has vast experience in designing and supervising agronomic greenhouse and field trials, especially on topics related to climate, trace gas emissions, fertilizer use, and water-management.

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Bjoern Ole Sander works as a climate change specialist at the International Rice Research Institute, under the Soil, Climate, Water Cluster-Sustainable Impact Platform. Dr. Sander is an expert in analyzing the GHG balance of different cropping systems, evaluating different mitigation options through water, fertilizer and crop residue management, and identifying suitable conditions to support dissemination of mitigation technologies.

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Contents

Acronyms

CH_4	Methane
CO_2	Carbon dioxide
CRDS	Cavity Ring-Down Spectroscopy
ECD	Electron-capture detector
FID	Flame ionization detector
GC	Gas chromatography
GHG	Greenhouse gas
N_2O	Nitrous oxide
OC	Organic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
TDLAS	Tunable diode laser for absorption spectroscopy

Introduction

Methane (CH_4) is one of the most important greenhouse gases (GHG) relative to climate change, as it contributes about 16% to the overall global increase in radiative forcing (IPCC, 2014). Considering man-made emission sources, paddy rice cultivation accounts for about 10% of all anthropogenic CH_4 emissions or about 1.5% of the total global anthropogenic GHG emissions (FAOSTAT, 2014; Nazaries et al., 2013). Among the most important variables controlling CH_4 production in rice fields are water management, fertilization with organic amendments, and rice variety (Conrad, 2002).

CH_4 production in rice fields originates from methanogenic archaea, decomposing organic matter in the absence of oxygen (O_2) (Conrad, 2009). Therefore, water management techniques influencing the soil redox potential of rice fields can help control or mitigate CH_4 emissions from paddy rice production (Itoh et al., 2011; LaHue et al., 2016). Aside from the absence of O_2 and other oxidants, the availability of soil organic matter (SOM) and ultimately, soil organic carbon (SOC), strongly influences the strength of CH_4 production in paddy rice fields. Incorporating rice straw into rice field soil can therefore intensify CH_4 emissions from rice fields (Yuan et al., 2014). However, the availabilities of O_2 and SOC are not only influenced by field management but also by the rice plant itself; hence, rice plants differ in terms of their effects on CH_4 production and the extent of these effects depends on the type of rice cultivar (Conrad, 2002).

Planting different rice cultivars can result in significant differences in the amount of CH_4 emitted. This was already observed in various pot and field studies, although most of these studies did not give a plausible explanation why such differences occur (Brye et al., 2016; Husin et al., 1995; Liou et al., 2003; Mitra et al., 1999; Riya et al., 2012; Zheng et al., 2014).

As for the studies that elaborated on the possible mechanism for the different emission rates from varieties, the reason behind these differences is commonly seen in morphological traits influencing plant structure, like aerenchyma or the root-shoot transition zone. In detail, rice plants influence not only the diffusion of CH_4 from the soil into the atmosphere through the plant aerenchyma, but also the diffusion of O_2 from the atmosphere into the root system and eventually, into soil around the root zone. Hence, some studies concluded that rice varieties with higher potential for gas transport through the aerenchyma or the root-shoot transition zone possess a higher potential for CH_4 emissions than other varieties (Butterbach-Bahl et al., 1997; Watanabe and Kimura, 1998).

Various other studies did not explicitly identify differences in aerenchyma as the cause of a higher CH_4 emission potential. Rather, they mentioned a higher average number of tillers or a higher vegetative growth in general and concluded that a higher abundance of tillers/higher vegetative growth leads to higher CH_4 transport rates to the atmosphere in rice cultivars (Aulakh et al., 2000, 2002, Das and Baruah, 2008a, 2008b; Gogoi et al., 2008; Gutierrez et al., 2013; Kerdchoechuen, 2005). An interesting side aspect of these results is the conclusion of one study, which emphasizes that unproductive tillers can negatively influence the CH_4 emission-per-yield ratio, as these lead to higher CH_4 transport rates while not contributing to grain yield (Wang et al., 2000).

Next to the above ground biomass, the root system of rice cultivars seems to play a more important role explaining differences in CH_4 emission potential. However, only one study correlated stronger root systems with lower CH_4 emission potential due to a higher transport and availability of O_2 in the soil resulting in higher CH_4 oxidation rates (Jiang et al., 2013). Other studies instead identified higher oxidase activity in rice roots then higher root biomass as the important variable for lower CH_4 emission potential connected to rice cultivars with stronger root systems (Ma et al., 2010; Satpathy et al., 1998; Wang et al., 2000)

In contrast, a larger number of studies (12 of a total of 27 studies identified by the literature research for this study (Annex 1) name the root system of rice plants as the main variable contributing to higher CH_4 emission potentials of rice varieties. This was mainly because roots provide substrate for CH_4 production by root exudation, sloughed-off cells and decay of roots (Conrad, 2002; Das and Baruah, 2008a, 2008b; Gutierrez et al., 2013; Jia et al., 2002; Kerdchoechuen, 2005; Lou et al., 2008; Lu et al., 2000; Su et al., 2015; Wang et al., 1997; Yao et al., 2000; Zhang et al., 2015) and of higher CH_4 conductance to the atmosphere (Yao et al., 2000). An interesting example showing the importance of differences in root exudates among rice cultivars was the study of Su et al. (2015). The study stated that adding a single transcription factor gene favored the allocation of photosynthates to above-ground biomass over allocation to roots. The altered allocation resulted in suppressed methanogenesis, possibly through a reduction in root exudates. Moreover, many of the above-mentioned studies connected rice cultivars with higher vegetative growth or above ground biomass to higher photosynthetic productivity, which ultimately leads to higher carbon transport into the soil via root exudates.

The studies listed clarified that differences in the emission potential of CH_4 among rice cultivars exist, but the exact variables causing these differences remain unclear. While the results of some of the studies were contradictory, root systems of rice plants and the source-strength they provide for methanogenesis in the form of C-substrate seem to be important variables. Regarding the number of rice varieties used in the twenty-seven studies mentioned, experiments usually included one to four rice varieties. Compared to the very large pool of existing rice cultivars today, the total number of rice cultivars tested for their CH_4 emission potential in existing published studies seems rather small. As the exact physiological plant traits influencing CH_4 emissions and causing differences among rice cultivars are not yet clearly identified and with most of them probably interacting with other plant traits and soil parameters, screening for specific plant traits to identify rice varieties with low CH_4 emission potential seems unfavorable.

1. Greenhouse gas sampling methods

1.1 Closed chamber measurements

Chamber-based measurements consist of chambers of a certain design (Fig. 1) placed over the soil surface to measure trace gas emissions from soils. The method has been used for many decades (Davidson et al., 2002), initially to measure carbon dioxide (CO_2) exchange. For trace gas emission measurements, for example CH_4 or nitrous oxide (N_2O), most commonly non-steady-state (also called “static chambers” or “closed chambers”) are used, which means that the flux is calculated from the rate of increase of measured gas concentration in the chamber headspace of known volume after the chamber is put over the soil.

Figure 1. Examples of different non-steady-state chamber designs (Photo sources: Sebastian Weller, Baldur Janz, Gasche, 2017a).

Non-steady-state chambers can be constructed with relatively low cost and work inputs, which will be important in emission screening and the large number of chambers needed for such experimental set-up. Important factors in constructing such chambers are: 1) use of a material inert to the measured gas species; 2) inclusion of vents to prevent pressure artefacts; and 3) choice of an appropriate chamber volume-to-area ratio. The chambers should be big enough to include the rice plant in our case. However, volume-to-area ratio should be small enough to permit measurement of the smallest flux of interest and large enough to minimize chamber disturbance effects. To provide sufficient air mixing inside the chamber headspace during measurements, fans can be installed inside the chamber. However, installation of fans is not mandatory, as it is disputable; if fans rather create artifacts by altering concentration gradients then avoid them, especially if air mixing is too excessive (Hutchinson et al., 2000; Le Dantec et al., 1999).

For sampling, chambers are fixed on a base frame, which is installed into the soil. The depth of frame installation depends on soil porosity and is generally between 2.5 and 10 cm. The gas tight sealing of chambers to the atmosphere and to the surrounding environment is required for measurements. The coupling of chamber and frame should be an airtight sealing as well, which is often achieved with a water barrier included in the base frame or with clamps. When designing the coupling, the fitting of the chambers should be quick and easy for swift preparation of the measurements and to avoid disturbance of the soil by strong movements of the base frame.

Gas samples from static chambers are normally taken with syringes with a volume of 50-100 ml. For this, chambers have to be equipped with lock-systems or rubber-septa. The general method is to transfer the air samples taken from inside the chamber headspace from the syringe into a vacuumed glass vial. Glass vials are then transferred into a gas chromatography (GC) laboratory and analyzed promptly for CH_4 content via a flame ionization detector (FID).

Figure 2. Examples of automated static chambers (Photo: S. Weller).

Regarding the emission screening of a large number of rice varieties, it should be considered that the measurement of one point/plant will produce 3-4 samples. That means, including replicates, every single measurement event of screening a large number of rice varieties will easily result in hundreds of vials, which have to be analyzed quickly to avoid bias. In planning, consider that it will require substantial amounts of material, manual labor, and laboratory capacity.

1.2 Automated chamber techniques

Static and chamber techniques can be coupled with automatic gas sampling and analysis systems, resulting in automated chamber systems. These systems are powerful tools for the *in situ* investigation of soil-atmosphere trace gas exchange and its response to changes in the environmental conditions. Furthermore, since monitoring takes place quasi-continuously (several measurements a day), these systems allow accurate surveillance of temporal dynamics of trace gas emissions and reliable detection of short-lasting events, which may be missed with manual sampling methods (Gasche, 2017b). Furthermore, because of the high sampling frequency, an automated system would provide a better assessment of CH_4 emission potential of rice cultivars than manual closed chamber measurements.

Automated chamber systems are used to produce GHG measurement data with high, timely resolution. Depending on the capacity of the system and the size of the experimental set-up (e.g. number of treatments, replicates), an automated system can produce, for example, as many as 12-24 measurements per chamber per day (Minamikawa et al., 2012; Yun et al., 2013), although 4-6 measurements per day are more common (Kiese and Butterbach-Bahl, 2002; Weller et al., 2016). In terms of sampling points/connected chambers, automated systems rarely exceed 15-20 sampling points/chambers because each sampling point/chamber has to be connected to the analytic unit (for example a gas chromatograph or laser) of the system. This is a limiting factor for the number of connected chambers because of sampling line length, sample connection slots, and control of chamber opening/closing and sampling.

Automated chambers are also usually expensive to produce—especially if a laser is used as an analytical unit—and require regular maintenance. Specifically, automated chambers need, for example, a pneumatic system for opening and closing and can cost up to 300-500 USD per piece with the need of a skilled engineer for production. Costs for a gas chromatograph, equipped with electron-capture detector (ECD) and FID detectors for CH_4 and N_2O measurements and a tunable diode laser for absorption spectroscopy (TDLAS) of targeted gas species range from 30.000-40.000 USD for a GC and 100.000-120.000 USD for a TDLAS or Cavity Ring-Down Spectroscopy (CRDS) laser analytical unit. In comparison, a chamber for manual sampling can be produced with material costs that are as low as 10-15 USD by relatively unskilled workers.

Furthermore, sampling time poses a problem in connecting a large number of sampling points. This is because a gas chromatograph needs at least 2-3 minutes to analyze one gas sample and the chamber closing time should be between 15-30 minutes with 3-4 samples for the measurement of a sufficient concentration increase in the chamber headspace. Using a laser as analytical unit enables almost real-time measurement of gas concentration and reduces sampling time significantly, but sufficient chamber closing times are still needed for flux computation. Therefore, the advantage of an (standard) automated GHG measurement system is high-frequency sampling of a few points with many measurements per day than the analysis of a large quantity of sampling points.For the emission screening with large number of varieties, an automated system, especially with a TDLAS or CRDS laser as analytical unit, could be recommended if the set-up of the system is adapted to the sampling of a large number of positions (short sample lines, high number of sample connection slots, sample control adapted to connection of high number of sampling points with high sampling frequency). However, system maintenance and control will be more expensive and demanding compared to manual sampling. Although, the total amount of manual labor will be lower. Moreover, it should also be noted that evaluation of flux data from an automated system will require specialized computing skills while evaluation of manual sampling is relatively easy in comparison.

Although experimental set-ups with large quantities of chambers are common in GHG studies, the assessment and sampling of CH_4 emissions from large numbers of rice cultivars (>100) present a challenge in terms of management of sampling and experimental design.

As the development of an applicable automated chamber system for this sort of screening is a challenging project and extremely demanding in terms of engineering skills and cost, we rather aim to recommend cheap and easy methods for constructing large quantities of (manual) static chambers and the best methods to reduce errors.

2. GHG sampling through manual closed chambers

2.1 Spatial heterogeneity

Before discussing the construction of chambers, spatial heterogeneity of fluxes has to be addressed. Measuring gas exchange under field conditions always brings the problem of spatial heterogeneity of fluxes, as soil is rarely homogenous and especially the production of N_2O and CH_4 tends to be localized in “hot spots” (Davidson et al., 2002). Because of this, we recommend the experimental set-up under greenhouse conditions with a prepared and homogenized soil. The soil used in preparing the

Figure 3. Soil homogenization with power weeder. (Photo: S. Weller)

seedbeds in the greenhouse should be taken from an established rice field to assure the abundance of methanogens. Soil should then be sieved (2mm) to ensure that it is homogenous and without any large organic materials (e.g. rice roots, etc.) or stones etc., which could influence gas exchange measurements. Further homogenization of all soil through mixing in a big container is recommended, by using a power weeder, for instance (Fig. 3). Homogenized soil can then be transferred into individual pots or a single large basin, such as a greenhouse or screen house.

According to various studies, it seems highly possible that the plant root system is the major factor explaining differences of CH_4 emission potential among rice cultivars. Certain studies therefore underline the importance of the carbon content of the soil used, as the delivery of carbon in the form of exudates is less important in a carbon-rich soil, while the transport of oxygen would be more important in a soil with higher carbon contents (Jia et al., 2002; Lu et al., 2000). Enhancing carbon in soil by adding starch, for example, seems therefore inadvisable as differences among rice cultivars could be blurred.

2.2 Time and duration of measurements

Aside from spatial heterogeneity, CH_4 emissions from rice fields can also differ significantly across measurements because of diurnal variations or observed fluctuations of different variables throughout the day. Multiple studies have shown that CH_4 emissions from rice paddy exhibit typical diurnal patterns with the highest emissions usually occurring from early to late afternoon (Weller et al., 2015 and sources therein). Although the exact variables leading to these variations are not identified, studies propose air temperature, soil temperature in varying depth (1–15 cm), as well as gross ecosystem photosynthesis and photosynthetically active radiation as the responsible factors (Chanton et al., 1997; Hatala et al., 2012; Yun et al., 2013).

Using automated chamber systems with sufficient sample frequency (min. 4-6 samples per day), the daily mean values are normally well-captured. However, as previously described, these systems are costly and difficult to develop, especially for a task like the screening of a large number of rice cultivars. For manual chamber measurements, the knowledge of diurnal patterns is of great importance for properly determining the daily mean values and for narrowing uncertainties of flux estimates at seasonal/annual scales. Measurements, carried out at times of the day when fluxes are supposed to be maximal or minimal, have been found to lead to pronounced over or underestimations of seasonal emissions in a range of ± 22–38% (Minamikawa et al., 2012; Yun et al., 2013).

However, studies also showed that diurnal variations do not always occur or are just pronounced during limited phases of rice plant growth and development (Weller et al., 2015). We therefore recommend to: 1) use a longer duration of chamber closing time (>1 h) to account for variation in CH_4 emissions, and more importantly, 2) measure during night-time, as variations of CH_4 emissions are normally weakly pronounced after sunset according to an IRRI study on diurnal variations (Fig. 4). As the goal of the proposed CH_4 emission screening is not to assess the average seasonal CH_4 emissions of the studied cultivars but to only define differences among them and identify the ones with highest CH_4 emission potential, this is the best method to use to avoid as much bias from diurnal variations as possible. A proof of concept of this approach is provided by Wassmann et al. (2018).

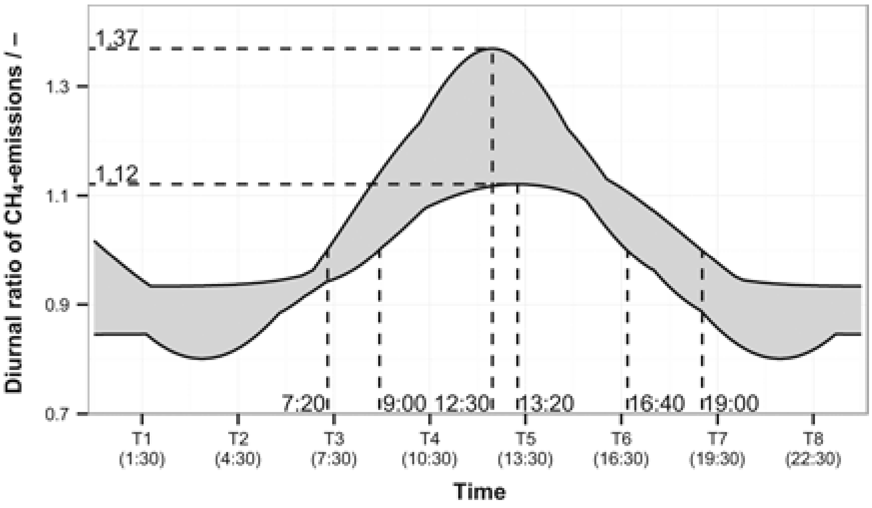

Figure 4. Uncertainty range of diurnal ratios of CH_4 emissions over various seasons from rice fields situated at IRRI, Los Baños, Philippines (Source: Weller et al., 2015)

2.3 Placement of chambers over flooded rice soil/rice plants

As CH_4 measurements in flooded rice fields can be easily influenced by forcing ebullition while attaching the measuring chamber to the base frame, chamber positioning should disturb the soil as little as possible. To secure an airtight coupling of chambers and base frame, the simple technique of water sealing can be applied. For water sealing, the floodwater of the rice field can be used by positioning the upper end of the base frame under the floodwater level. It should be tested beforehand if moving the floodwater leads to increased diffusion of CH_4 from floodwater. In addition, no handling of clamps and screws, etc. is needed with a water seal, which could lead to unwanted movement of the chamber and disturbance of the soil. Instead of a base frame, a grid made of metal or plastic can be used to position the chambers over the rice plant (Fig. 5 and 6).

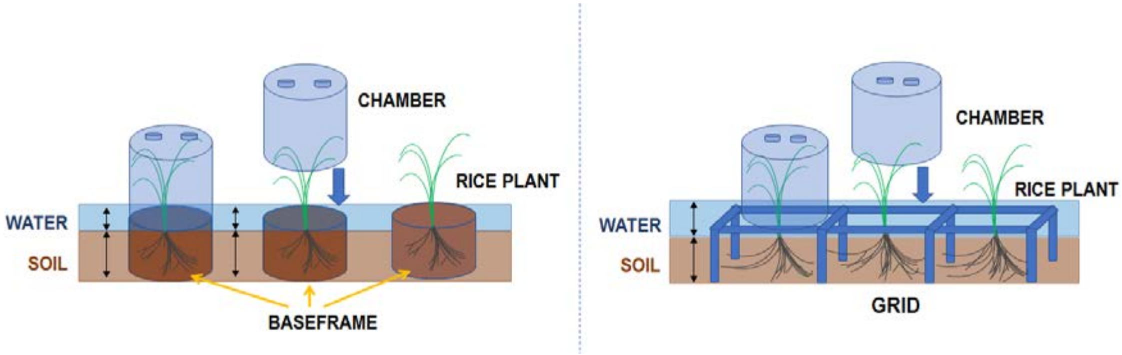

Figure 5. Chamber positioning with base frame or grid.

As many studies highlight the importance of the root system for CH_4 production in rice plants, it should be assured that no interaction among the root systems of different rice cultivars takes place. This can be achieved by using either the base frame to enclose the root system or the grid with a wider planting distance (e.g. > 40 cm). However, it should be noted that rice plants may extend their root system farther than 40 cm, especially if soil moisture is low during some periods. Therefore, we recommend the use of base frames wherein plants are directly transplanted at the beginning of the study. This is to avoid interaction of the root systems among different rice cultivars during the experiment. Frames should be sufficiently large (diameter >20 cm) to allow more or less unhindered root growth.

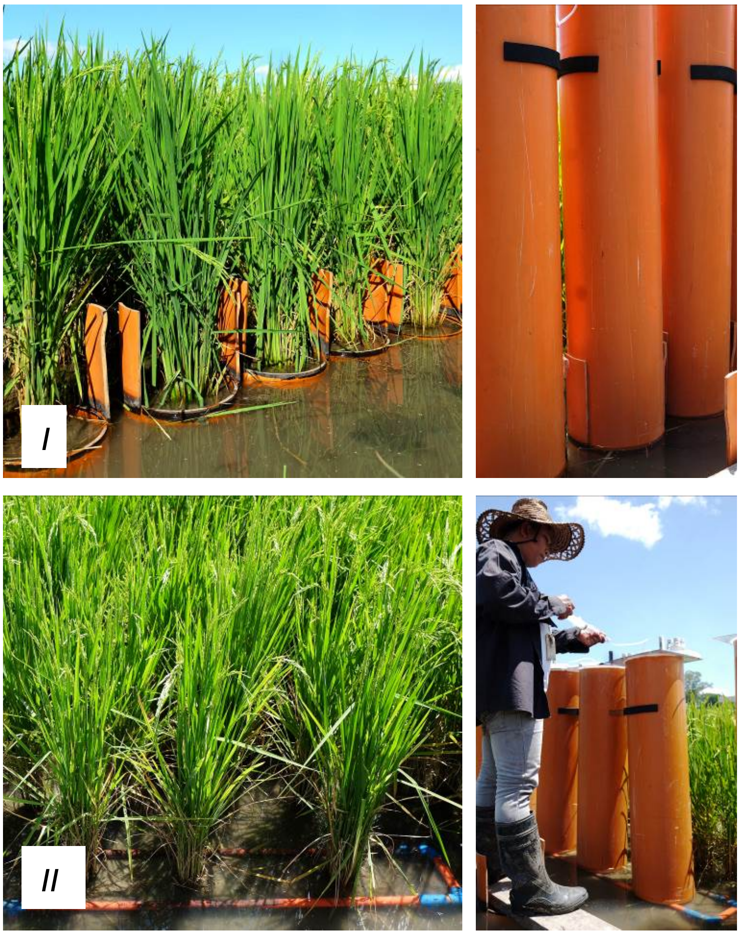

Figure 6. Example of a grid made of PVC-pipes / connectors. Grid can be placed over one or various plants under flood water level (I.), then GHG measurement chamber is positioned on grid with flood water (blue box) serving as seal (II). Photo credits: Camille Pelaez and Philline Felicilda/IRRI

2.4 Screening of a large number of rice varieties

Manual closed chambers can be easily produced using materials such as plastic containers or buckets. However, as large number of chambers needs to be produced for the screening of more than a hundred rice cultivars, the base material should be available in sufficient quantities. PVC pipes are accessible in hardware stores all over the world and can be easily modified into closed chambers.

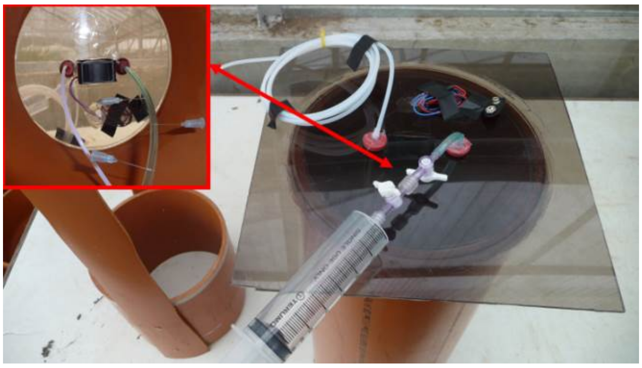

Figure 1. Modified waste-water pipe with base frame and detail of the inside of the pipe/chamber.

Materials to be used should be tested beforehand to ensure that there are low/no sorption properties for the aimed gas species. This can be tested by inserting a standard gas with known gas concentration into the sealed chamber and taking samples after longer time periods (e.g. 12h, 24h). If gas concentrations do not change, this means that the chamber is airtight and has no sorption properties. Chambers should be equipped with a rubber septum for sampling and a vent for pressure equalization. A fan for mixing air volume in chamber headspace is optional. However, a longer sampling tube reaching inside the chamber headspace, which can be used for air mixing by sample syringe before air samples are taken, may serve the same purpose if chamber headspace volume is not too large.

PVC water pipes are easily accessible and can be cut into chamber headspace and base frame parts (Fig. 4-8) with handheld tools (for example, with an angle grinder). As the coupling system for the larger pipes (>8") is not suited for easy handling, pipes modified into chambers can just be positioned loosely on top of pipe part acting as base frames, with the flood water as an airtight seal. A small support can be installed onto base frames for more stable positioning of chambers. To follow plant growth, 50-cm and 100-cm chambers can be constructed and used according to plant height. Lids for the pipe parts acting as chambers can be cut out from acrylic sheets and easily glued on with silicone rubber. Lids can be modified with septa for pressure equilibration and sampling, a 12V fan for air mixing, and a 9V/12V battery connection. As described above, every single position/plant needs a base frame, but chambers can be easily switched between positions. However, this means that a large number of base frames have to be cut and produced. As 8-in pipes are smaller in inner diameter (only 18.5 cm), it is recommended to use at least 10-in pipes with an inner diameter of 23.5 cm to ensure unhindered plant root growth.

Figure 8. Example of chambers made of a waste-water pipe and stackable plastic containers.

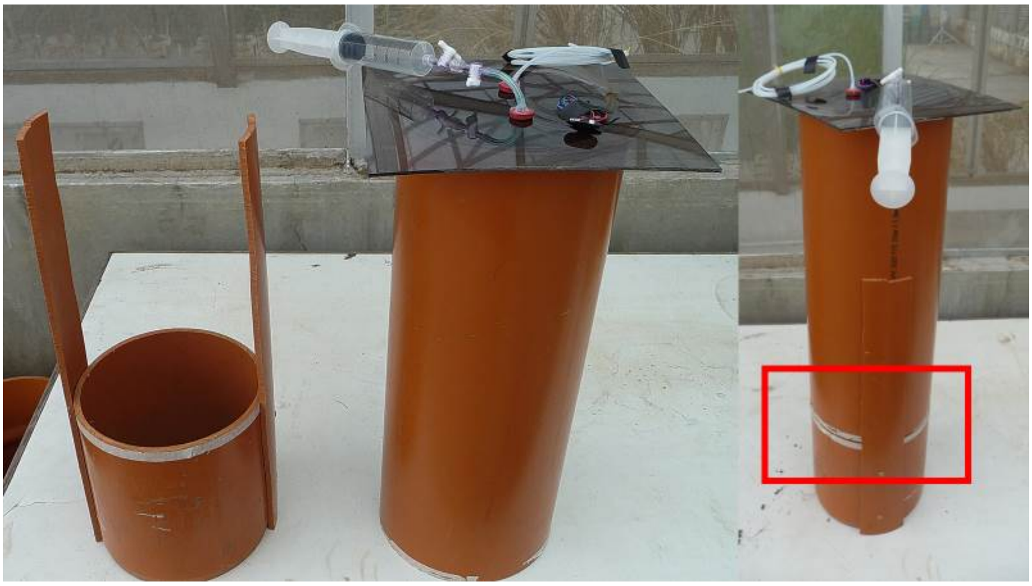

Figure 9. 20-cm base frame and 50-cm modified pipe/chamber (left) and the two parts connected (right). Upper part is just loosely placed above base frame (red box).

Figure 2. Chamber positioned in a basin with rice soil and plants and in comparison, with a GHG measurement chamber made of plastic containers. Detail of base frame connection under flood water level (red box).

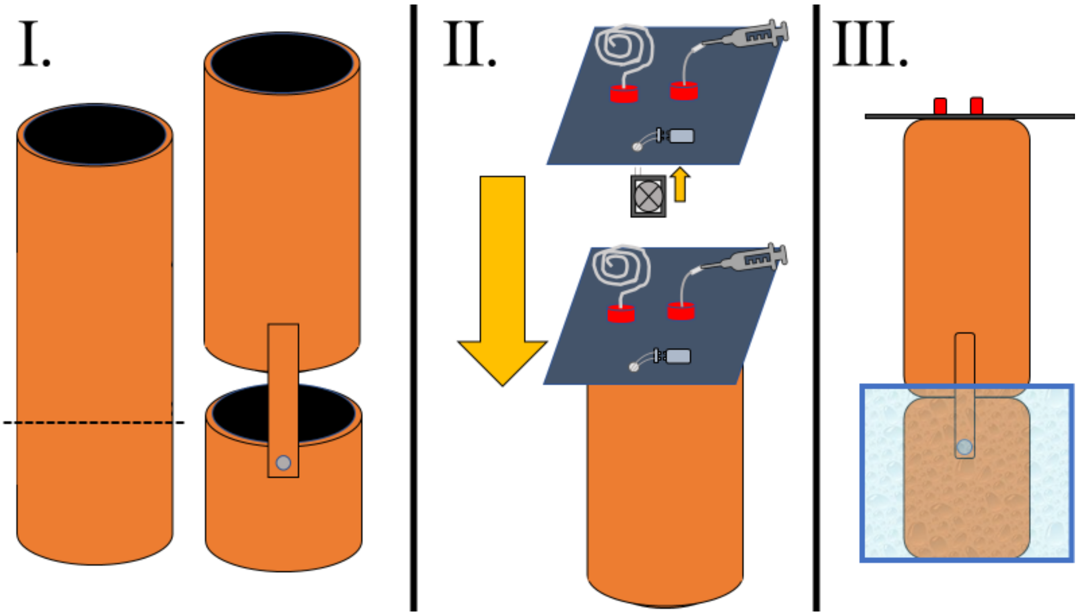

Figure 3. Schematic of chamber design/modified waste-water pipe. Pipe is cut into a 20-cm base frame and a 50-80-cm chamber. Base frame has short arms attached to the sides to support chamber part on top (I.). Acrylic sheet with septa and fan/9V battery is glued on as lid (II.). Flood water serves as water-seal (III.)

3. Literature Study

Literature Database: Effect of rice cultivar/variety on CH_4 emissions

Extensive literature research on common scientific databanks (e.g. ScienceDirect, Scopus, Web of Science) identified a total of 27 studies (conducted from 1995 to 2016), which included the difference of CH_4 emissions among different rice cultivars/varieties as a part of their research.

Although some of these studies did not explain the effects of plant trait on CH_4 emissions, many of them (12 out of 27 studies) explained these differences via positive correlations of root parameters with CH_4 emissions. Although the exact physiological plant traits influencing CH_4 emissions and causing differences among rice cultivars in this regard are not yet clearly identified, this review of existing studies emphasize the importance of root systems, and especially root exudates, as a cause for differences in CH_4 emissions. An example showing the importance of differences in root exudates among rice cultivars is the study of Su et al. (2015). Based on this study, the addition of a single transcription factor gene favored the allocation of photosynthates to aboveground biomass over allocation to roots. The altered allocation resulted in suppressed methanogenesis, possibly through a reduction in root exudates. Table 1 summarizes the findings of the literature study.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
6	Aulakh	2000	Biomass	X	Results on plant traits affecting CH_4 emissions: Tiller number is a major controlling factor of plant-mediated CH_4 transport rates in widely different cultivars. Therefore, plants with less biomass and fewer tillers could minimize CH_4 emission.	In tall, dwarf, and NPT cultivars, increase in root or aboveground biomass during initial growth determines a corresponding increase in methane transport capacity.
10	Aulakh	2002	Biomass growth above ground (until flowering)	X	Results on plant traits affecting CH_4 emissions: In all cultivars, tiller numbers were linearly related to MTC indicating that the number of outlets determines CH_4 transport.	The results suggest that in inbred cultivars representing tall, dwarf and NPT groups, an increase in root or aboveground biomass during plant growth until flowering determines the corresponding increase in methane transport capacity (MTC). Further increase or any change in plant biomass at maturity does not affect MTC. However, in the case of hybrids, a positive relationship of MTC with root, shoot, and total plant biomass including grain indicate continuous development of aerenchyma with plant growth resulting in enhanced MTC.
16	Das	2008	Crop photosynthetic rate	X	Results on plant traits affecting CH_4 emissions: Both CH_4 and N2O emission exhibited a significant positive correlation with leaf area, leaf number, tiller number and	Variety Gitesh emitted the least N2O and CH_4 amongst all the rice varieties.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
					root dry weight. Methane emission showed significant positive correlations with soil temperature and crop photosynthetic rate. Traditional rice varieties with profuse vegetative growth recorded higher CH_4 and N2O fluxes compared to HYVs.	
2	Butterbach-Bahl	1997	Gas permeability aerenchyma	X	Results on plant traits affecting CH_4 emissions: Gas permeability of aerenchyma and root-shoot transition zone are the main sites of resistance to plant-mediated gas exchange between the soil and the atmosphere.	The Roma variety emitted more CH_4 than the Lido variety.
21	Gutierrez	2013	Gas transport capacity (?)	X	Results on plant traits affecting CH_4 emissions: None.	Methane fluxes were correlated in highly positive and negative manner with methanogens and methanotrophs abundances, respectively ($P < 0.05$), but not with any of the apparent plant growth parameters. These suggest that CH_4 emissions may be directly affected by the substrate-producing potential and gas transport capacity of each cultivar rather than the external plant growth variables.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
10	Aulakh	2002	Inbred cultivars	Hybrid cultivars	Results on plant traits affecting CH_4 emissions: In all cultivars, tiller numbers were linearly related to MTC indicating that the number of outlets determines CH_4 transport.	The results suggest that in inbred cultivars representing tall, dwarf and NPT groups, an increase in root or aboveground biomass during plant growth until flowering determines the corresponding increase in methane transport capacity (MTC). Further increase or any change in plant biomass at maturity does not affect MTC. However, in the case of hybrids, a positive relationship of MTC with root, shoot, and total plant biomass including grain indicate continuous development of aerenchyma with plant growth resulting in enhanced MTC.
27	Brye	2016	Inbred cultivars	Hybrid cultivars	Results on plant traits affecting CH_4 emissions: None.	Inbred cultivars accounted for 55 to 70% more CH_4-C emissions than hybrid cultivars.
13	Liou	2003	Indica	Japonica	Results on plant traits affecting CH_4 emissions: none.	In the first crop season, there were significant increases of 3.1–3.7 folds in methane emission fluxes due to planting of Indica rice. In comparing two rice varieties, the Indica rice variety showed a tendency for larger methane emission than the Japonica rice variety in the second crop season.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
23	Zheng	2014	Indica (YS GWP)	Japonica (YS GWP)	Results on plant traits affecting CH_4 emissions: None.	Our results showed that significantly higher yield-scaled GWP occurred with Indica rice varieties (1101.72 kg CO2 equiv. Mg-1) than japonica rice varieties (711.38 kg C O2 equiv. Mg-1)
1	Husin	1995	IR-64 variety	Cisadane variety	Results on plant traits affecting CH_4 emissions: none	The IR-64 variety emitted more CH_4 than the Cisadane variety
15	Das	2008	Leaf area	X	Results on plant traits affecting CH_4 emissions: results suggest that in “Agni”, enhanced diversion of photosynthates to roots resulted in more substrate being available to methanogenic bacteria in the rhizosphere. Additionally, the more extensive vegetative growth of this cultivar may enhance methane transport from the soil to the above-ground atmosphere.	Traditional cultivar, “Agni”, and improved modern cultivar, “Ranjit”, were grown in light textured loamy soil under irrigation. A higher seasonal integrated methane flux (Esif) was recorded from “Agni” compared to “Ranjit”.
17	Gogoi	2008	Leaf area index	X	Results on plant traits affecting CH_4 emissions: Methane flux values of the crop-growing season exhibited a positive correlation with leaf number, tiller number, and leaf area index. Traditional rice cultivars with profuse vegetative growth recorded higher methane flux values compared with high-yielding varieties.	Variety IR 36 was found to emit the least methane amongst all the cultivars.
5	Mitra	1999	Pusa 933 cultivar	Pusa 169 cultivar	Results on plant traits affecting	The Pusa 933 variety emitted

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
					CH_4 emissions: none	more CH_4 than the Pusa 169 variety.
25	Qin	2015	Rice straw biomass	Grain yield	Results on plant traits affecting CH_4 emissions: Results suggest that organic source strength provides the substrate of methane production while the oxidation potential in the rhizosphere and the methane transport capacity of rice roots and culm dominate the emissions of methane from soil to the atmosphere.	Methane emissions were found to be significantly ($p < 0.05$) and positively correlated with tiller number, culm biomass and soil organic matter, dissolved soil organic carbon and total carbon content, but negatively correlated ($p < 0.05$) with rice harvest index (HI), and root and panicle biomass.
15	Das	2008	Root allocated photosynthesis	Photosynthates allocated to panicle	Results on plant traits affecting CH_4 emissions: results suggest that in “Agni”, enhanced diversion of photosynthates to roots resulted in more substrate being available to methanogenic bacteria in the rhizosphere. Additionally, the more extensive vegetative growth of this cultivar may enhance methane transport from the soil to the above-ground atmosphere.	Traditional cultivar, “Agni”, and improved modern cultivar, “Ranjit”, were grown in light textured loamy soil under irrigation. A higher seasonal integrated methane flux (Esif) was recorded from “Agni” compared to “Ranjit”.
10	Aulakh	2002	Root biomass growth (until flowering)	X	Results on plant traits affecting CH_4 emissions: In all cultivars, tiller numbers were linearly related to MTC indicating that the number of outlets determines CH_4 transport.	The results suggest that in inbred cultivars representing tall, dwarf and NPT groups, an increase in root or aboveground biomass during plant growth until flowering determines the corresponding increase in methane transport capacity

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
						(MTC). Further increase or any change in plant biomass at maturity does not affect MTC. However, in the case of hybrids, a positive relationship of MTC with root, shoot, and total plant biomass including grain indicate continuous development of aerenchyma with plant growth resulting in enhanced MTC.
3	Wang	1997	Root dry weight	X	Results on plant traits affecting CH_4 emissions: Differences in methane emission rates were determined by the differences in source strength of methanogenic materials. High correlation between methane emission -root dry weight /root dry weight - total carbon released from roots.	Newly developed high-yielding plant type 'IR65598' had the lowest methane emission rates.
25	Su	2015	Root exudates	Root exudate reduction	Results on plant traits affecting CH_4 emissions: The altered allocation resulted in an increased biomass and starch content in the seeds and stems, and suppressed methanogenesis, possibly through a reduction in root exudates.	The addition of a single transcription factor gene conferred a shift of carbon flux to SUSIBA2 rice, favoring the allocation of photosynthates to aboveground biomass over allocation to roots. Three-year field trials in China demonstrated that the cultivation of SUSIBA2 rice was associated with a significant reduction in methane emissions

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
						and a decrease in rhizospheric methanogen levels.
11	Conrad	2002	Root exudation	X	Results on plant traits affecting CH_4 emissions: Rice cultivars with more root exudation also tend to emit more CH_4.	It is the interaction between the various microorganisms which eventually determines the rate of CH4 production over time.
18	Lou	2008	Root exudation	X	Results on plant traits affecting CH_4emissions: The differences in average daily CH4 fluxes among the cultivars were related to different root exudation as DOC content, root length and tiller number.	Average daily CH4 fluxes varied with the cultivars in the sequence, Dular ≧ IR72>IR65598 ≧ Koshihikari. Dissolved organic C (DOC) content in the soil differed among the cultivars, in the sequence IR72 > Dular > Koshihikari > IR65598.
12	Jia	2002	Root exudation	X	Results on plant traits affecting CH_4 emissions: The contribution of rice plants to CH_4 production seems to be more important than to rhizospheric CH_4 oxidation and plant-mediated transport in impact of rice plants on CH_4emission.	Multiple regression analyses showed that CH_4emission flux was positively related with CH_4 production rate and rice plant-mediated CH_4 transport efficiency, but negatively with rhizospheric CH_4 oxidation (R2=0.425 for Yanxuan, P<0.01; R2=0.426 for 72031, P<0.01; R2=0.564 for 9516, P<0.01).
21	Gutierrez	2013	Root exudation	X	Results on plant traits affecting CH_4 emissions: None.	Methane fluxes were correlated in highly positive and negative manner with methanogens and methanotrophs abundances, respectively (P < 0.05), but not with any of the apparent plant

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
						growth parameters. These suggest that CH_4 emissions may be directly affected by the substrate-producing potential and gas transport capacity of each cultivar rather than the external plant growth variables.
9	Yao	2000	Root fresh weight (CH_4 conductance)	X	Results on plant traits affecting CH_4 emissions: Higher CH_4 conductance is generally related to plants with larger root volume, heavier root fresh weight.	CH_4 conductance is positively correlated with parameters of plant size.
14	Kerdchoechuen	2005	Root fructose / acetic acid contents	X	Results on plant traits affecting CH_4 emissions: At ripening stage, root glucose content was higher in CN1 while root fructose and acetic acid contents were higher in SP1. Shoot and root weights at the different growth stages were also consistently higher in SP1 and CN1 (high- CH_4 emitters) than in SP60 and SP90 (low- CH_4 emitters).	Thai cultivars Supanburi 1 (SP1), Supanburi 60 (SP60), Supanburi 90 (SP90) and Chainat 1 (CN1) were used. CH_4 flux rates were comparably higher in CN1 and SP1 than in SP60 and SP90.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
14	Kerdchoechuen	2005	Root glucose contents	X	Results on plant traits affecting CH_4 emissions: At ripening stage, root glucose content was higher in CN1 while root fructose and acetic acid contents were higher in SP1. Shoot and root weights at the different growth stages were also consistently higher in SP1 and CN1 (high- CH_4 emitters) than in SP60 and SP90 (low- CH_4 emitters).	Thai cultivars Supanburi 1 (SP1), Supanburi 60 (SP60), Supanburi 90 (SP90) and Chainat 1 (CN1) were used. CH_4 flux rates were comparably higher in CN1 and SP1 than in SP60 and SP90.
18	Lou	2008	Root length	X	Results on plant traits affecting CH_4 emissions: The differences in average daily CH_4 fluxes among the cultivars were related to different root exudation as DOC content, root length and tiller number.	Average daily CH_4fluxes varied with the cultivars in the sequence, Dular ≧ IR72>IR65598 ≧ Koshihikari. Dissolved organic C (DOC) content in the soil differed among the cultivars, in the sequence IR72 > Dular > Koshihikari > IR65598.
15	Das and Baruah	2008	Root volume	Grain yield-attributing parameters	Results on plant traits affecting CH_4 emissions: results suggest that in “Agni”, enhanced diversion of photosynthates to roots resulted in more substrate being available to methanogenic bacteria in the rhizosphere. Additionally, the more extensive vegetative growth of this cultivar may enhance methane transport from the soil to the above-ground atmosphere.	Traditional cultivar, “Agni”, and improved modern cultivar, “Ranjit”, were grown in light textured loamy soil under irrigation. A higher seasonal integrated methane flux (Esif) was recorded from “Agni” compared to “Ranjit”.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
9	Yao	2000	Root volume (CH_4 conductance)	X	Results on plant traits affecting CH_4 emissions: Higher CH_4 conductance is generally related to plants with larger root volume, heavier root fresh weight.	CH_4 conductance is positively correlated with parameters of plant size.
14	Kerdchoechuen	2005	Root weight	X	Results on plant traits affecting CH_4 emissions: At ripening stage, root glucose content was higher in CN1 while root fructose and acetic acid contents were higher in SP1. Shoot and root weights at the different growth stages were also consistently higher in SP1 and CN1 (high- CH_4 emitters) than in SP60 and SP90 (low- CH_4 emitters).	Thai cultivars Supanburi 1 (SP1), Supanburi 60 (SP60), Supanburi 90 (SP90) and Chainat 1 (CN1) were used. CH_4 flux rates were comparably higher in CN1 and SP1 than in SP60 and SP90.
7	Lu	2000	Root zone DOC dynamics	X	Results on plant traits affecting CH_4 emissions: The inter-cultivar difference in root C releases is responsible for the inter-cultivar difference in DOC production, and consequently in CH_4 flux.	The release of root exudates increased in the order: IR65598 (new plant type) < IR72 (modern cultivar) < Dular (a traditional cultivar). Correspondingly, DOC concentrations in the root zone and CH_4 emission rates increased.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
26	Zhang	2015	Root (?) below ground CH_4 production	Root (?) below ground CH_4 oxidation	Results on plant traits affecting CH_4 emissions: Results suggest that organic source strength provides the substrate of methane production while the oxidation potential in the rhizosphere and the methane transport capacity of rice roots and culm dominate the emissions of methane from soil to the atmosphere.	Methane emissions were found to be significantly ($p < 0.05$) and positively correlated with tiller number, culm biomass and soil organic matter, dissolved soil organic carbon and total carbon content, but negatively correlated ($p < 0.05$) with rice harvest index (HI), and root and panicle biomass.
15	Das	2008	Root length	X	Results on plant traits affecting CH_4 emissions: results suggest that in “Agni”, enhanced diversion of photosynthates to roots resulted in more substrate being available to methanogenic bacteria in the rhizosphere. Additionally, the more extensive vegetative growth of this cultivar may enhance methane transport from the soil to the above-ground atmosphere.	Traditional cultivar, “Agni”, and improved modern cultivar, “Ranjit”, were grown in light textured loamy soil under irrigation. A higher seasonal integrated methane flux (Esif) was recorded from “Agni” compared to “Ranjit”.
14	Kerdchoechuen	2005	Shoot weight	X	Results on plant traits affecting CH_4 emissions: At ripening stage, root glucose content was higher in CN1 while root fructose and acetic acid contents were higher in SP1. Shoot and root weights at the different growth stages were also consistently higher in SP1 and CN1 (high- CH_4 emitters) than in SP60 and SP90 (low- CH_4 emitters).	Thai cultivars Supanburi 1 (SP1), Supanburi 60 (SP60), Supanburi 90 (SP90) and Chainat 1 (CN1) were used. CH_4 flux rates were comparably higher in CN1 and SP1 than in SP60 and SP90.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
21	Gutierrez	2013	Substrate-producing potential (?)	X	Results on plant traits affecting CH_4 emissions: None.	Methane fluxes were correlated in highly positive and negative manner with methanogens and methanotrophs abundances, respectively ($P < 0.05$), but not with any of the apparent plant growth parameters. These suggest that CH_4 emissions may be directly affected by the substrate-producing potential and gas transport capacity of each cultivar rather than the external plant growth variables.
6	Aulakh	2000	Tiller number	X	Results on plant traits affecting CH_4 emissions: Tiller number is a major controlling factor of plant-mediated CH4 transport rates in widely different cultivars. Therefore, plants with less biomass and fewer tillers could minimize CH_4 emission.	In tall, dwarf, and NPT cultivars, increase in root or aboveground biomass during initial growth determines a corresponding increase in methane transport capacity.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	**Author**	**Year**	**CH_4 correlated**		**Research results**	**Conclusion**
			Positively	**Negatively**		
15	Das	2008	Tiller number	X	Results on plant traits affecting CH_4 emissions: results suggest that in "Agni", enhanced diversion of photosynthates to roots resulted in more substrate being available to methanogenic bacteria in the rhizosphere. Additionally, the more extensive vegetative growth of this cultivar may enhance methane transport from the soil to the above-ground atmosphere.	Traditional cultivar, "Agni", and improved modern cultivar, "Ranjit", were grown in light textured loamy soil under irrigation. A higher seasonal integrated methane flux (Esif) was recorded from "Agni" compared to "Ranjit".
17	Gogoi	2008	Tiller number	X	Results on plant traits affecting CH_4 emissions: Methane flux values of the crop-growing season exhibited a positive correlation with leaf number, tiller number, and leaf area index. Traditional rice cultivars with profuse vegetative growth recorded higher methane flux values compared with high-yielding varieties.	Variety IR 36 was found to emit the least methane amongst all the cultivars.
18	Lou	2008	Tiller number	X	Average daily CH_4 fluxes varied with the cultivars in the sequence, Dular $\geqq$ IR72>IR65598 $\geqq$ Koshihikari. Dissolved organic C (DOC) content in the soil differed among the cultivars, in the sequence IR72 > Dular > Koshihikari > IR65598.	Results on plant traits affecting CH_4 emissions: The differences in average daily CH_4 fluxes among the cultivars were related to different root exudation as DOC content, root length and tiller number.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	Author	Year	CH_4 correlated		Research results	Conclusion
			Positively	Negatively		
8	Wang	2000	Unproductive tillers	Root oxidative activity	Results on plant traits affecting CH_4 emissions: Rice cultivars with few unproductive tillers, small root system, high root oxidative activity, and high harvest index are ideal for mitigating CH_4 emission in rice fields.	Use of cultivar, Zhongzhuo (modern japonica), reduced CH_4 emission by 56% and 50%, in 1995 and 1997, respectively, as compared with Jingyou (japonica hybrid) and Zhonghua (tall japonica)
17	Gogoi	2008	Vegetative growth	X	Results on plant traits affecting CH_4 emissions: Methane flux values of the crop-growing season exhibited a positive correlation with leaf number, tiller number, and leaf area index. Traditional rice cultivars with profuse vegetative growth recorded higher methane flux values compared with high-yielding varieties.	Variety IR 36 was found to emit the least methane amongst all the cultivars.
4	Satpathy	1997	X	Root tip oxidase activity	Results on plant traits affecting CH_4 emissions: Negative correlation of root oxidation potential on CH_4 flux.	Of the several variables studied (root region redox potential, above- and underground biomass, grain and straw yield, duration of the crop, percent area occupied by the air space and root oxidase activity), only oxidase activity of the root tip exhibited a significant (negative) correlation with CH_4 flux indicating an indirect effect of root oxidation potential on CH_4 flux.

Table 1. Studies (1995-2006) on the difference of CH_4 emissions among different rice cultivars/varieties.

ID #	**Author**	**Year**	**CH_4 correlated**		**Research results**	**Conclusion**
			Positively	**Negatively**		
19	Ma	2010	X	Methanotrophs growth in rhizosphere	Results on plant traits affecting CH_4 emissions: The results suggest that hybrid rice stimulates the growth of methanotrophs in the rice rhizosphere, and hence enhances CH_4 oxidation that attenuates CH_4 emissions from the paddy soil.	Hybrid rice produced 50–60% more of shoot biomass than Indica and Japonica cultivars. However, the emission rate of CH_4 was similar to Japonica and lower than Indica.
20	Riya	2012	X	Biomass (leavestar variety)	Results on plant traits affecting CH_4 emissions: None.	The lowest GWPs per ton of above-ground biomass were found to be from the ‘Leaf Star’ cultivar, which had a higher aboveground biomass than other cultivars.
22	Jiang	2013	X	Root system (strong)	Results on plant traits affecting CH_4 emissions: Strong root system contributed mainly to lower CH4 emission.	According to the relationships between the plant growth characteristics and the CH_4 emission, a stronger root system contributed mainly to the lower CH_4 emission of Ningjing 1, as compared with Zhendao 11.
22	Jlang	2013	X	Super rice variety	Results on plant traits affecting CH_4 emissions: Strong root system contributed mainly to lower CH_4 emission.	According to the relationships between the plant growth characteristics and the CH_4 emission, a stronger root system contributed mainly to the lower CH_4 emission of Ningjing 1, as compared with Zhendao 11.

4. Conclusion/Recommendations

This report has documented various studies which found differences in methane (CH_4) emission potential of different rice cultivars which include field management, type of rice cultivar, soil organic matter content, differences in aerenchyma, number of tillers, and root system. But existing literature indicate experiments involving generally one to four rice varieties only, which is relatively small considering the large pool of existing rice cultivars. Thus, this research provides recommendations for the screening of a large number of rice varieties to identify cultivars with low CH_4 emission potential.

For the emission screening with large number of varieties, an *automated system* could be recommended; however, this would entail high costs and system maintenance, and would require specialized computing skills in evaluating flux data. On the other hand, *manual sampling* is less expensive, with data evaluation being relatively easy compared with the automated system. Using the manual closed chambers in GHG sampling, the differences between the (1) base frame and (2) grid for chamber positioning are compared in Table 2.

Table 2. Comparative difference of the base frame and grid.

Base frame		**Grid**	
Pro	***Contra***	***Pro***	***Contra***
• Enclosed root system • With support chambers sit very stable on frame • Airtight connection can also be made above floodwater level	• Hindered root growth? • Each position needs one base frame	• Free root growth • After a grid covering all position is installed, chambers can be switched easily between positions	• Interactions between root systems of different cultivars? • Chamber positioning less stable? • Airtight connection only possible if grid sits under floodwater level • Larger planting distances are necessary to avoid root interactions

In deciding which method is best to apply, consider some of these guidelines:

- Chamber positioning should cause minimal disturbance to the soil to avoid ebullition.
- To secure an airtight coupling of chambers and base frame, water sealing can be applied.
- It should be assured that no interaction between the root system of different rice cultivars takes place. The base frame proves effective in enclosing the root system but if the grid method is opted, make sure to have ample, wider planting distances.

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