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REVIEW ARTICLE

Greenhouse Gas Emissions from Rice Fields in Indonesia: Challenges for Future Research and Development

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Abstract Rice is an essential crop in Indonesia, but it also contributes to greenhouse gas (GHG) emissions. Although several aspects of rice that increase productivity have been well studied and documented, studies are exploring its environmental aspects, including GHG emissions, are still lacking. More research may have been conducted, but only a few studies have been published in peer-reviewed journals. Robust data on GHG emissions from rice fields in Indonesia is still lacking, including factors affecting it and technology to reduce GHG emissions. Publications of GHG emissions research in Indonesia have been downloaded from several search engines, including ScienceDirect and Google Scholar, and searches using certain keywords. These reviewed publications reveal that research has only been conducted within controlled environmental settings. Thus, this review focuses on studies that have been carried out in Indonesia and other countries and assesses water regimes, rice varieties, fertilizer, soil types, and organic matter on GHG emissions in rice fields. More research into factors controlling GHG emissions in rice fields (e.g., water management, rice cultivar, soil types, and fertilizer) is still needed. This review identifies knowledge gaps concerning future research and development in Indonesia. The research should meet the needs, either national or global strategies to cope with climate change, develop sustainable farming practices, which will only succeed if there are government policies. Therefore, this research should involve an intensive interdisciplinary approach that includes both researchers and other stakeholders.

1. Introduction

The relationship between Earth's increasing temperature and greenhouse gas (GHG) emissions has been widely acknowledged, and the increase in GHG emissions due to anthropogenic sources has been recognized since the eighteenth century (Forster et al., 2007). The atmospheric concentration of methane (CH_4) and nitrous oxide (N_2O) were 1,803 ppb and 324 ppb in 2011, respectively. This significantly exceeded pre-industrial levels from 1750 by 150% and 20%, respectively (Intergovernmental Panel on Climate Change [IPCC], 2013; Wang et al., 2017). In 2020, these levels reached the concentration of 1,875 ppb CH_4 and 323 ppb N_2O (Butter & Montzka, 2020). This rapid increase of GHG concentration has resulted in Earth's temperature increases, which has led to global warming and a changing climate. A changing climate has a range of potential ecological, physical, and health impacts, including extreme weather events, rising sea levels, altered crop growth, and effects on human health. Agriculture is one of these significant sources of GHG emissions because it contributes about 13% of global anthropogenic emissions. CH_4 and N_2O were two primary GHG emissions that were created from agriculture-related activities. These gases contributed about 60% and 38% of total global GHG emissions (IPCC, 2013; Zhao et al., 2019). Furthermore, CH_4 and N_2O were responsible for the Earth becoming warmer because their global warming potential is 23 and 298 times greater than CO_2, respectively (Signor & Cerri, 2013). Rice cultivation is the second major source of CH_4 emissions from agriculture, after CH_4 from enteric fermentation. Rice cultivation contributes 493–723 Mt CO_2e year^{-1} to global CH_4 emissions (Smith et al., 2014).

Rice is a staple food for more than half of the world's population (Haque et al., 2014). Thus, to meet the world's growing population, rice production is expected to increase by 24% in 2030 (Food and Agricultural Organization [FAO], 2009). This will cause a more rapid increase in GHG emissions from agriculture. In 2014, 31% of global rice-harvesting areas were in South East Asia; this constituted about 48 million hectares (FAO, 2017). CH_4 is produced from flooded rice fields by anaerobic bacteria in a hypoxic condition (Cicerone & Oremland, 1988; Chunmei et al., 2018). N_2O is produced from the soil through nitrification-denitrification processes that relate to microbial activity in the presence of nitrogen (N) (Butterbach-bahl et al., 2013;

Denmead et al., 2010). Emission from inorganic fertilizer increased by an average of 3.9% year^{-1} from 1961–2010 (Tubiello et al., 2013). Seventy percent of these emissions were created by Asian rice cultivation. Eighty million hectares, or about 75% of the world's rice production, were managed by irrigated rice, which is found mostly in Indonesia, Vietnam, the Philippines, and Thailand (FAO, 2017). In tropical areas, irrigated rice crops can be planted during two or three cropping seasons each year.

Field measurements of N_2O emissions from soil were initiated in the 1950s, and field measurements of CH_4 began in the early 1980s (Cicerone and Oremland, 1988; Oertel et al., 2016). These measurements presented robust data that increased understanding of how each gas's biogeochemical cycles affected environmental factors. In early 1990, mitigation became a major focus, alongside the Kyoto Protocol in 1992. Since then, a wealth of research has explored the relationship between CH_4 and N_2O emissions and rice fields mitigation. Enhanced understanding of the processes involved in CH_4 and N_2O emissions from irrigated rice resulted in further research that focused on how to reduce these emissions without decreasing the rice yield. As anthropogenic sources, CH_4 and N_2O emissions from rice are complex processes that involve both natural conditions and a management system. The production, oxidation, and transport of CH_4 combine to form the total CH_4 emissions from a rice field (Frenzel et al., 1999; Wang et al., 2017). Methanogenesis is the process responsible for CH_4 production by methanogenic bacteria in anaerobic zones (Horwarth, 2011; Smith et al., 2018), and methanotroph bacteria can oxidize over 50% of the CH4 produced under aerobic conditions. N_2O is a by-product of nitrification-denitrification by soil bacteria during the production of ammonium and nitrate (Horwarth, 2011). Factors affecting CH_4 and N_2O emissions from rice fields include plant physiology; the soil's physical, biological, and chemical properties, temperature; the soil's redox potential; and pH (Pathak et al., 2005; Wang et al., 2017). These factors are driven by management practices, such as the water regime, organic amendments, fertilizer use, tillage, and variety of rice (Horwarth, 2011; Luo et al., 2013; Wang et al., 2017).

Recent research into GHG emissions from rice fields has mostly focused on Asia, particularly China, India, Japan, the Philippines, and Thailand. Since there are considerable spatial and temporal variations in GHG emissions from soils (Butterbach-bahl et al., 2013), field measurements must be conducted in various areas to eliminate these variations. According to FAO (2017), Indonesia has the largest irrigated rice area, which requires robust field-measurement data on GHG emissions from rice. Agricultural statistics from the Ministry of Agriculture of Indonesia (MOA, 2016) report the rice harvested are to be 13.8 million hectares in 2016 (Fig. 1). The highest harvested area for CH_4 emissions from rice fields was on the island of Java (Fig. 1). According to the national GHG inventory (2017), average emissions from rice fields in Indonesia was 0.18 t CH_4 ha^{-1}. However, research into GHG emissions in rice fields is limited, so GHG emissions' contribution is not well documented in peer-reviewed publications. Peer-reviewed publications are paramount importance once research has been completed.

The Intergovernmental Panel on Climate Change (IPCC) has developed guidelines to calculate GHG emissions at the country level, based on categories for reporting to the United Nations Framework Convention on Climate Change (UNFCCC). These guidelines provide default emission factors for global needs, which are generated from a database of published literature (Wang et al., 2018). However, since GHG emissions from rice fields result from complex interactions between climatic conditions, soil properties, and management practices, the IPCC encourages countries to generate local emission factors to obtain more accurate and reliable GHG emissions measurements. Since each country has specific climate and soil conditions, each has established field measurements that are addressed in this review. Yagi et al. (2019) has reviewed gaps for southeast Asian countries. The authors state that the review can help formulate strong

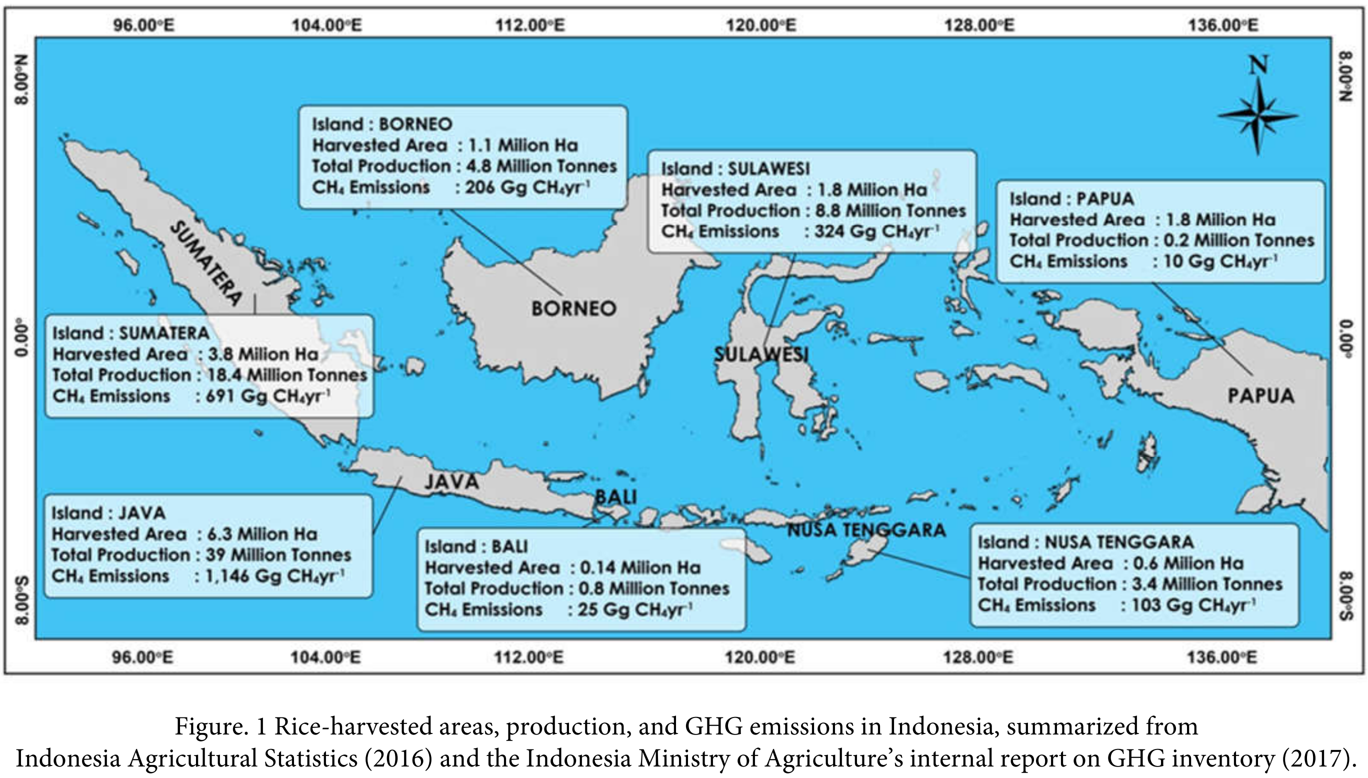

Figure. 1 Rice-harvested areas, production, and GHG emissions in Indonesia, summarized from Indonesia Agricultural Statistics (2016) and the Indonesia Ministry of Agriculture's internal report on GHG inventory (2017).

Figure. 2. Automatic chamber installation at Indonesian Agricultural Environment Research Institute, Jakenan, Central Java.

policy and mitigation measures. Thus this review is conducted to have more focuses and assess research that has already been conducted in Indonesia, based on published literature. It also explores this same focus in other countries, particularly in terms of the effect of water regimes, rice varieties, fertilizer, soil types, and organic matter on GHG emissions from rice fields. This provides a gap analysis that can be utilized for future research and development.

Current research on GHG emissions in Indonesia and other countries

The effect of water regimes on GHG emissions from rice fields

The ways in which water-regime practices affect CH_4, and N_2O emissions from rice fields is already well known (Yagi & Minami, 1990; Bouwman, 1991; Sass et al., 1992). Flooded conditions are profitable for CH_4 production in soil (Adhya et al., 2000; Yan et al., 2005; Ma et al., 2010), but the production does not immediately occur after flooding. Instead, it takes time to reduce the molecular oxygen and electron acceptors that are trapped in the soil pores. Methanogenesis will take place after the soil is moist enough or under a redox value of between 150–200 mV or 70%–80% of water-filled-pore space (Jain et al., 2004). Therefore, the duration of flooding and drying, either during or prior to crop establishment, is important (Horwarth, 2011). Continuous flooding (CF) during a whole season produces the highest CH_4 emissions, compared to multiple opportunities for drainage, mid-season drainage, intermittent irrigation, early-season drainage, or alternate wetting and drying (AWD), yet shown the opposite in N_2O emissions (Wang et al., 1999; Yan et al., 2000; Jain et al., 2004; Zou et al., 2005; Peyron et al., 2016; Carrijo, et al., 2017; Oo et al., 2018). Although mid-season drainage during rice growth reduces CH_4 emissions (Wang et al., 1999), this is less than with two periods of drainage (Yan et al., 2000). Early-season drainage reduces CH_4 emissions by 35.7%, while AWD reduces emissions by 52.8% (Oo et al., 2018). In 2013, the International Rice Research Institute (IRRI) proposed safe AWD as an alternative irrigation technique that could reduce rice paddies' high water consumption. This is also expected to reduce CH_4 emissions by 70%.

Setyanto et al. (2018) carried out a three-year field experiment to measure AWD's feasibility under local environmental conditions in a tropical region. The research was conducted during wet and dry seasons in Jakenan, Central Java, and it investigated AWD in terms of GHG emissions, rice productivity, and water use. Three water-management treatments were tested: CF, flooding when the natural water level declined 15 cm below the soil surface (defined as AWD), and site-specific AWD (AWDS). Gas measurements were conducted on a weekly basis. The results revealed that both AWD and AWDS reduce CH_4 emissions by 35% and 38%, respectively, compared to CF. AWD and AWDS also both reduced total water use. However, there were no significant differences in seasonal N_2O emissions and grain yield.

In Indonesia, irrigated rice areas covered approximately 4.8 million hectares in 2016, and they had yearly growth of 0.6% (MOA, 2016). When water is sufficiently available, which is highly supported in technical and semi-technical irrigated rice, farmers tend to manage their fields in a CF condition. Since 2007, the government has introduced intermittent irrigation for rice cultivation as a water-saving measure, alongside other intensification techniques. One of these intensification techniques is the System of Rice Intensification (SRI) concept, which was introduced in 2008. Water-management research into GHG emissions in Indonesia was first initiated by Nugroho et al. (1994) in Taman Bogo, Lampung, South Sumatra. This research combined chemical N fertilizer with an organic fertilizer, which was arranged in a split-plot design. The main plot was for water management (CF and intermittent irrigation), while three subplots only applied chemical N fertilizer and three plots applied both chemical fertilizer and organic material (rice straw, *sesbania rostrata*, or cow manure) at a rate of 5 t ha^{-1}. The results suggest that neither water nor fertilizer management create emissions. However, this research was only conducted over the course of one season, so variations between seasons remain unknown. Other research shows differences in total emissions between dry and wet seasons.

Husin (1994) conducted research in West Java that combined water management (CF, intermittent flooding, and saturated soil) and two rice varieties (Cisadane, IR64). This research concluded that water management and rice variety both strongly affect diurnal and seasonal CH_4 emissions. CH_4 gas samples were taken on a weekly basis at three times of day (3–5 am, 7–9 am, and 1–3 pm). Soil temperature at a depth of 5 cm also strongly affects the diurnal variation. The intermittent system suppressed emissions by 50% without reducing the grain yield, whereas saturation suppressed 70% of emissions but slightly reduced the yield. This research also found that ambient CH_4 concentration was higher at an early stage of the rice-growing period (around 6.7 ppmv), compared to the fallow period (around 1.7 ppmv).

Lumbanraja et al. (1997) also investigated the effect of water management (CF and rainfed) combined with a chemical fertilizer and rice straw during two rainy seasons. Rice-straw application increased CH_4 emissions, both in irrigated and rainfed rice, but rainfed rice emitted 27%–37% less CH_4 than the CF rice field.

Comprehensive research has also been conducted by Setyanto et al. (2000). This long-term study was conducted in Jakenan, Pati, Central Java, between 1993 and 1998, which is a total of ten rice-growing seasons and incorporates both dry and wet seasons. Since an automatically closed chamber was used, the data were quite smooth. Gas samples were captured and analysed every four minutes for 24 hours during the rice-growing season. Seasonal CH_4 emissions were two-fold higher in irrigated fields than in rainfed fields. The impact of organic manure was relatively small in rainfed rice during the dry season, but rice straw increased emissions by 40% in the wet season. There was also a trend toward higher CH_4 emissions from organically fertilized plots than from mineral-fertilized plots. Early-maturing rice cultivars had the lowest

Table 1. Population of denitrifying bacteria in continuously flooded (CF) and intermittently drained (ID) plots in South Kalimantan (Hadi et al., 2010).

Soil depth (cm)	Denitrifying bacteria (×10^5 MPN g^{-1} soil)	Denitrifying bacteria (×10^5 MPN g^{-1} soil)
	CF	ID
0–5	6.4 B	5.6 c
5–10	1.6 B	5.0 bc
10–15	9.8 B	1.8 b
15–20	0.2 A	0.4 a

Numbers followed by the same capital letter are not different between depth in CF-treatment, while numbers followed by the same small letter are not different between depths ID-treatment according to Fisher's LSD test.

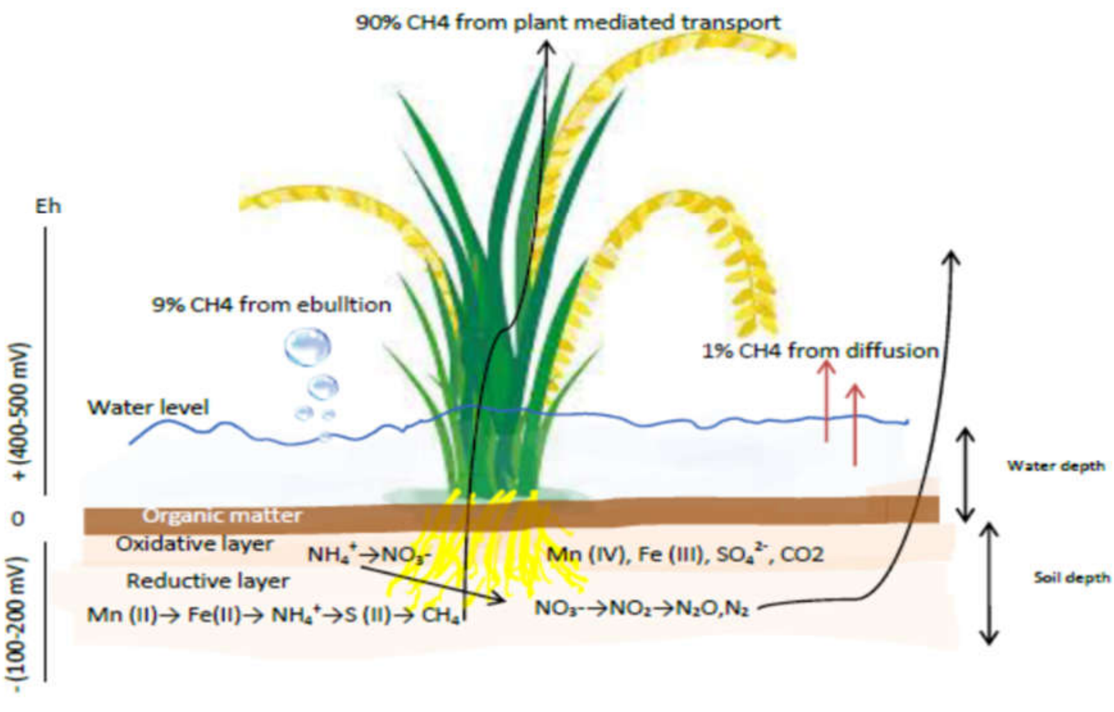

Figure 3. Graphic depicting methane release from a rice field.

emissions compared to late-maturing rice cultivars. The authors concluded that increasing the growing days of a cultivar increased the emissions emitted, which resulted in high seasonal emissions.

Hadi et al. (2010) conducted research in Japan and South Borneo, Indonesia, to determine water management's impact on CH_4 and N_2O emissions and on microbial properties. These authors suggested that intermittent irrigation suppressed GHG emissions without any significant changes in the soil's microbial population. The study focused on rice fields comprised of alluvial soil. Intermittent irrigation was performed with seven-day intervals, starting at the tillering or heading stages and continuing until harvesting. As stated by many other researchers, the soil redox potential indicated the production of CH_4. A high redox potential limits CH_4 production by methanogens, as shown in the plot that underwent intermittent irrigation. Furthermore, soil depth affected denitrifying bacteria population, as the fewest were found in the lowest soil depth (15–20 cm).

The effect of rice varieties on GHG emissions from rice fields

Rice crops play an essential role in releasing CH_4 from soil into the atmosphere. Previous studies have indicated that CH_4 emissions are up to 20 times higher from soil that is planted with rice than from unplanted soil (Nouchi & Mariko, 1993; Dannenberg & Conrad, 1999; Brye et al., 2017), which illustrates rice plants' significant role in emissions. Three mechanisms release CH_4 from soil into the atmosphere: diffusion through floodwater, ebullition, and plant-mediated diffusion (Smart et al., 2016). Many researchers have stated that around 90% of methane from rice fields is released through rice cells via aerenchyma (which acts as a chimney), while 8%–9% is released by ebullition, and only 1%–2% is released through diffusion (Holzapfel-pschorn et al., 1986; Schutz et al., 1989; Nouchi et al., 1990; Neue & Sass, 1994; Butterbach Ball et al., 1997; Le Mer & Roger, 2001). It is illustrated in Figure 3.Varying GHGs emissions from rice varieties are reported in several studies conducted in China, Japan, India, Italy, and the United States of America (Lindau et al., 1994; Ball et al. 1997; Bhattacharyya et al., 2019; Brye et al., 2017). Some varieties emitted less CH_4 than other varieties, depending on their characteristics. This led to the suggestion that selected varieties should be used to reduce methane emissions. A study by Gogoi et al. (2008) demonstrated that traditional rice cultivars with a longer vegetative growth stage produced higher methane fluxes than high-yielding varieties. Baruah et al. (2010) also showed that high-yielding rice varieties emitted less CH_4 and N_2O than traditional varieties. These GHG emissions significantly positively correlate with leaf area, leaf number, tiller number, and the root's dry weight.

There are hundreds of registered and (mostly local) unregistered rice varieties in Indonesia, including varieties for upland rice, certain pest and disease resistance, and certain levels of stress resistance (e.g., drought, floods, acidity). Research into low methane rice varieties in Indonesia currently focuses on the identifying phase, and there is little research into the breeding phase.

In 1997, Nugroho et al. measured the effect of eight popular rice varieties in Indonesia at that time. These rice varieties were Bengawan Solo, IR 74, IR 64, Atomita 4, Cisanggarung, Way Seputih, Kapuas, and Walanai. The authors stated that differences in CH_4 emissions among these rice varieties were affected by the amounts and constituents of root exudates and root systems, as well as by activities leading to oxidization of the root environments. Wihardjaka (2007) also measured rice cultivar's effect, but this study specifically focused on a rainfed rice field. Seven rice varieties with different maturity were tested. The moderate-duration varieties included IR 64, Cisantana, Sintanur, and Way Apo Buru, while the short-duration varieties included Dodokan and Silugonggo. The study also tested Mentik, which is a local deeper-duration variety. All the varieties received the same amount and type of fertilizer. Agronomic measurements were then performed, such as plant height, tiller number, and root weight. Way Apo Buru emitted less methane than the other six varieties, and it had a relatively high yield. Wihardjaka and Sarwoto (2015) tested another eight new rice varieties: Inpari 14, Inpari 15, Inpari 17, Inpari 18, Inpari 20, Ciherang, Situ Bagendit, and IR 64. Inpari 18 had the lowest CH_4 emissions, while Inpari 15 had the highest. Inpari 18 and Inpari 17 had the higher yields.

The effect of fertilizer on GHG emissions from rice fields

Fertilized agricultural soil contributes to 38% of annual global N_2O emissions (IPCC, 2013; Zhao et al., 2019). Increased N, both in the form of organic and synthetic fertilizers, has increased this anthropogenic source of N_2O. The amount of N transforms during nitrification and denitrification processes, which then increases during these activities. This ultimately leads to higher levels of N_2O emissions (IPCC, 2013). N_2O emissions from anthropogenic N inputs produces both direct pathways (i.e., directly from the soil to which N is added) and indirect pathways through volatilization of compounds such as NH_3 and NO_X. This also subsequently occurs during redeposition, as well as through leaching and runoff (IPCC, 2013).

Some studies have indicated that the application of different levels of synthetic urea fertilizer can increase CH_4 emissions. For instance, meta-analysis data has shown that adding high levels of N (with an average of 249 kg N ha^{-1}) can decrease CH_4 emissions by 15%, while adding a low level of inorganic fertilizer N (with an average of 79 kg N ha^{-1}) can increase CH_4 emissions by 18% and this is also relative to instances in which no N fertilizer is applied (Adviento-Borbe & Linquist, 2016; Linquist et al., 2012; Xie et al., 2009). Other studies suggest that applying synthetic fertilizer decreases CH_4 emissions, compared to organic fertilizer (Yuan et al., 2018), that adding nitrogen decreases CH_4 emissions compared to not adding N, or that there are no significant relationship exists (Bronson et al., 1997; Wang et al., 1993).

Nitrogen fertilizers are the most popular agents in rice production because they increase grain yields. Urea and ammonium sulphate are two forms of N fertilizers, and they account for 80%–90% of the total demanded by rice cultivation (Food and Agriculture Organization, http://apps.fao.org/). Other fertilizers that are used in rice production, such as silica or iron materials in any form, also play a role in the rice yield and in GHG emissions. Linguist et al. (2012) report that applying sulphate fertilizers at average rates of 208 and 992 kg S ha^{-1} reduces CH_4 emissions by 28% and 53%. CH_4 emissions can be significantly reduced by 40% if urea replaced by ammonium sulphate at the same N rate, but this action may increase N_2O emissions. The application of steel slag fertilizer with a high silica content could also reduce CH_4 emissions (Ali et al., 2008; Susilawati et al., 2015). Using dicyandiamide (DCD) or other nitrification inhibitors leads to lower emissions of both CH_4 (−18%) and N_2O (−29%) (Linguist et al., 2012). Limited field measurements also indicate that fertilizer placement at either the soil surface or more deeply (deep placement) also brought contradictory results in terms of CH_4 and N_2O emissions. These findings suggest that the impact of synthetic fertilizer on GHG emissions might differ, depending on management practices utilized across the rice field.

Nugroho et al. (1994) measured CH_4 emissions from a paddy field in Taman Bogo, Lampung that had been subjected to several fertilizers. There were six plots, three of which were chemical fertilizers plots (Urea+ $(NH_4)_2SO_4$, Urea, and $(NH_4)_2SO_4$) and three of which were modified with urea and organics materials (rice straw, *sesbania rostrata*, and cow dung manure). CH_4 emissions from the plots that included organic materials were relatively higher than plots that only used chemical fertilizer. The effects of organic fertilizers on CH_4 emissions and rice yields were less prominent because the plots still used urea. This research also found that CH_4 was mainly emitted (more than 50%) in the first half of the rice-growth period, due to the high temperatures experienced in the tropics (Indonesia).

Wihardjaka (2010) investigated the effect of rice straw and nitrification inhibitors on N_2O emissions for rainfed lowland rice. The study was conducted during the 1999 dry season in Jakenan, Pati, Central Java. The field experiment was designed as a factorial randomized block with three replication and two factors of treatments related to rice straw (without rice straw, fresh straw, and composting straw) and nitrification-inhibitor materials (without nitrification inhibitor, neem cake, and carbofuran). Interactions between rice straw and nitrification-inhibitor materials decreased N_2O emissions significantly in a lowland rainfed rice field. The application of neem cake and carbofuran decreased N_2O emissions by 48.6% and 41.3%, respectively.

Susilawati et al. (2015) investigated the effects of steel slag applications on CH_4 and N_2O emissions, as well as on the rice yield, using two major Indonesian soil types (Inceptisols and Vertisols). Steel slag is a by-product of the steel industry that contains high levels of iron, silica, and calcium. These materials act as electron acceptors in the redox system, while organic C acts as the electron donor (Burgin et al., 2011). The study took place at two different sites that use Inceptisols and Vertisols soil, and it was conducted during both dry and rainy seasons. The first experiment (during the dry season) consisted of two treatments (control and steel slag at 1 t ha^{-1}), and the steel slag in the second experiment (rainy season) was split into two subplots that accommodated the additional 1 and 2 t ha^{-1} steel slag. All the treatments were replicated five times. Overall, although steel-slag application tended to decrease CH_4 emissions at both sites, there was no significant difference. The application of 1 and 2 t ha^{-1} steel slags in Inceptisols from Jakenan decreased CH_4 emissions by 9.1% and 18.7%, respectively. There was also evidence that N_2O emissions decreased at both sites during the rainy season. This decreased by 34 and 38% for Inceptisols and Vertisols, respectively, after application of t ha^{-1} steel slags. The rice yield also increased by 4.8%–5.6% in Jakenan and by 0.3%–5.6% in Wedarijaksa. There was a significant difference in CH_4 and N_2O emissions between both sites and, therefore, between soil types. The amount of oxidizing agent in the soil is a critical factor in reducing CH4 emissions in flooded rice fields, so it is important to maintain the plow layer's oxidative conditions.

Wihardjaka and Poniman (2015) measured sulfur's contribution to rice productivity and atmospheric GHG in lowlands. In this study, applying sulphur-containing fertilizers led to competition on hydrogen between methane-producing bacteria (methanogens) and sulphate-reducing bacteria. This subsequently inhibited methane production. The formation of sulphate ions, which is a by-product of ZA (ammonium-sulphate fertilizer) hydrolysis, slows the potential decrease in soil redox. This is due to the oxidation process of sulphites to sulphates, during which the soil Eh (redox potential) tends to be high. For methanogen, sulphate and sulphite are toxic. ZA fertilization in paddy fields reduces methane emissions by 25%–35% (Jain et al., 2004), but nitrogen fertilization inefficiency leads to high N_2O emissions. However, applying S-containing fertilizer in the form of ZA or S-elements suppresses the release of N_2O. Thus, applying S-elements (S^0) with 115 kg N ha^{-1} to rainfed lowland rice in Central Java reduced N_2O emissions by 45%–52%. The use of sulphur-coated urea fertilizer increased N fertilization efficiency and reduced the release of N_2O.

The effect of soil types on GHG emissions from rice fields

Soil-type characteristics play the most significant role in GHG-emissions production. Studies have shown that different soil types' original conditions produce different amounts of GHG emissions (Lindau et al., 1991; Minami, 1995; Watanabe & Kimura, 1999; Huang et al., 2002; Wang et al., 2017). The soil texture and clay mineralogy both affect the percolation rate, which ultimately affects CH_4 emissions in waterlogged paddy soils. Additionally, soil cracks that occur during clay soil's drying period help release trapped CH_4. Field measurements by Yagi and Minami (1990) stated that CH_4 emissions decreased in peaty soils, alluvial soils, and andosols. Other soil properties (e.g., total N, soil texture [clay and sand fractions], CEC, available K, and active Fe content) all significantly affect potential methane production in the topsoil and subsoil (Mitra et al., 2002).

Regulation of CH_4 and N_2O production and consumption in soil is also determined by the availability of electron acceptors and donors (Ro et al., 2011). Electron acceptors (e.g., Fe^{3+}, NO_3^-, and sulphate) are reduced during anaerobic periods, and they are regenerated (oxidized) during aerobic periods (Neubauer et al., 2007). Soil also provides the carbon substrates that microbes need to produce CH_4 and N_2O and to enhance plant growth.

Subadiyasa et al. (1997) measured methane emissions from paddy fields in Bali that had soil from volcanic ash to ascertain the influence of rice straw, fertilizer application, and rice varieties. This experiment took place in Gianyar (Inceptisols) and Tabanan (Alfisols) using a factorial design and three replications. The treatments focused on the application of rice-straw (S0: without straw, S1: with 5 t ha^{-1} straw), the inorganic fertilizer used (F0: without inorganic fertilizer, F1: 250 kg urea + 100 kg TSP [Triple Superphosfat] + 50 kg KCl ha^{-1}), and the rice variety (V1: IR 64, V2: local variety of Krueng Aceh). There were no significant differences in methane emissions between the two rice varieties, but methane emissions were significantly higher in the plot treated with rice straw than in the plot without rice straw. This was the case both with and without inorganic fertilizer in both places. Total emissions tended to be higher with Tabanan (Alfisols) than with Gianyar (Inceptisols). This was also true for grain yields, regardless of the rice variety.

Setyanto et al. (2002) conducted research to investigate the potential of CH_4 production in selected soil types in Java. The authors determined the limiting factors of CH_4 production, and they tested 11 soils types based on FAO soil classifications (brown Regosol, red Latosol, dark-brown alluvial, grey-yellowish alluvial, brown Latosol, grey Hydromorph Association, dark-gray Grumosol, brown-reddish Mediterranean, dark-brown Mediterranean, dark-gray Grumosol and Lithosol Association, and brown-greyish Grumosol). To ascertain potential production, soil samples were measured using the incubation method on a laboratory scale. There were two treatments: the potential CH_4 production in soil with original organic matter and with the addition of reducible carbon sources (glucose to enhance their CH_4 production capacity). The result of the potential CH_4 production from soil with original organics sources was then divided into three groups. The highest potential CH_4 production capacity ranged from 7.75–37.66 mg CH_4 kg^{-1} (gray-yellowish alluvial and gray Hydromorph Association), the medium-capacity ranged from 0.44–3.54 mg CH_4 kg^{-1} (brown-greyish Grumosol, red Latosol, dark-gray Grumosol and Lithosol Association, brown Latosol, and dark-brown alluvial), and the low capacity ranged from 0.19–0.28 mg CH_4 kg^{-1} (dark-gray Grumosol, dark-brown Mediterranean, brown-Regosol, and the brown-reddish Mediterranean). After glucose was added, the groups were changed, all the soil types showed an increase of potential CH_4 production at least 12 times, compared to the untreated soils. The dark-gray Grumosol produced the highest CH_4 level, while the brown-greyish Grumosol produced the lowest level. This finding demonstrates that the soil's chemical and physical properties significantly influence CH_4 production. Adding an organic substrate also changed the potential production due to the soil properties. Subsequently, stepwise multiple regression analysis of CH_4 production potential and soil properties showed that the soil's pH strongly influences CH4 production; the Fe_2O_3, MnO_2, and SO_4 content; and silt. This finding indicates that the potential CH_4 production of soil with original organic matter can differ after the addition of other substrates.

Wihardjaka and Harsanti (2011) conducted almost identical research to Setyanto et al. (2002). However, Wihardjaka and Harsanti used different soil types: namely, Grumosol, Mediterranean, Nitosol, alluvial, and Planosol. Additionally, CH_4 production potential was not grouped in the same way as in the Setyanto et al. study. CH_4 production from the above soils ranged from 0.05–0.96 mg CH_4 g $soil^{-1}$. When the group was categorized according to Setyanto's criteria, there was low-to-medium potential production. The ways in which the soil's properties influenced CH_4 production differed from the previous study. The Wihardjaka and Harsanti study found out that the contents of P_2O_5, K_2O, SO_4^{2}-, and pH significantly increase CH_4 production, whereas soil iron content was negatively correlated.

The effect of organic matter on GHG emissions from rice fields

Organic amendments have been widely accepted to improve soil fertility for global rice production. In addition to improving soil fertility and enhancing crop productivity, the application of organic matter in the soil triggers processes such as the priming effect, methanogenesis, nitrification, and denitrification, all of which lead to GHG emissions (Thangarajan et al., 2013). Methanogenesis is the production of CH_4 by microbes (methanogens) in the soil, which occurs under anaerobic conditions. Nitrification and denitrification are two contrasting microbial processes in the soil's N cycle, and they can lead to N_2O emissions. Organic amendments in any form provide a source of readily available C and N, which is believed to induce higher CH_4 emissions and influence N_2O emissions (Bouwman et al., 2002; Cicerone et al., 1992; Huang et al., 2004; Humphreys et al., 2019; Janz et al., 2019; Yang & Chang, 2000).

Despite the relationship between organic matter and GHG emissions, adding organic matter to soil is also important because it enriches soil organic carbon (SOC), which is associated with soil organic matter (SOM). SOM is the organic fraction of the soil that is made up of decomposed plant and animal materials, as well as microbial organisms in a stable form. Agricultural soil is one of five world carbon pools, and it is estimated to have soil C stock of 2,400 gigatons for 2 m of soil depth ($2{,}400 \times 10^{15}$ g) (Batjes, 1996). SOC sequestration has been considered a possible means of mitigating climate change because this takes atmospheric CO_2 and converts it into longer-life soil carbon (Lal, 2003, 2004). A small increase in soil C stocks is believed to play a role in mitigating GHG emissions because the soil can store two to three times more carbon than the atmosphere (Minasny et al., 2017).

The application of organic material in agricultural cultivation practices has been integrated into Indonesia's government policies over the last ten years. The government

Table 2. Significant differences on GHG emissions and rice yields between OM treatments

Organic matter application	CH_4 (kg/ha/season)	Yield (t/ha)
Compost 5 t/ha	252.6 a	3.5 a
Rice straw 5 t/ha	445.3 ab	3.2 a
Bio-compost 5 t/ha	167.3 b	3.4 a
Without OM	195.0 b	2.8 a

Values in each column are the mean of five replications. Different letters presented vertically indicate significant differences between means at P = 0.01, according to Tukey's HSD test.

has given this as a subsidies policy in the form of well-decomposed organic matter (e.g., compost). Although farmers' practices often involve using plant residue as an organic fertilizer, some also practice biomass burning. Organic farming has also become famous among Indonesian farmers. Many studies have been conducted that focus on modifying organic matter. A three-year study of an experimental plot was conducted by Setyanto and Kartikawati (2011) to measure the effect of an entirely organic farming practice, compared to a mix organic–inorganic fertilized farming. The results showed that using a high level of organic fertilizer, combined with intermittent irrigation, has the lowest global warming potential (GWP). However, this also resulted in the lowest yield. Ariani et al. (2017) investigated the effect of different types of organic fertilizer on GHG emissions and yield over the course of three rice-growing seasons. These authors found a significant difference ($p < 0.01$) when 5 t ha^{-1} rice straw was added, compared to compost, bio-compost, or without OM. However, they failed to find a significant difference in yield. After three seasons, rice straw increased the highest SOC content by 2%, while compost and bio-compost only resulted in 1% of SOC increase.

Challenges for future research and development in Indonesia

In recent years, the number of studies into GHG emissions and agriculture in Indonesia has grown, but there is still a lack of peer-reviewed papers. As this country is comprised of thousands of islands, there is substantial spatial variability in terms of microclimates, ecosystems, and cultures. This condition has also led to substantial differences in farmers' practices. Agricultural GHG emissions currently contribute about 6% and 13% to the Indonesia's GHG emissions (including and excluding Land Use and Land Use Change and Forestry [LULUCF], respectively) (Ministry of Environment and Forestry [MoEF], 2017). Several mitigation options have been introduced in Indonesia, but gaps remain. Thus, research should focus on but not limit itself to explorations of high sources of emissions, such as rice cultivation, N_2O emissions from managed soil, and enteric fermentation (three of the IPCC's [2013] 11 categories of GHG emissions from agriculture). Furthermore, research should identity feasible mitigation strategies and technologies that maintain or increase rice productivity.

Managing rice fields by alternating anaerobic and aerobic conditions using various water regimes is a recognized means of significantly reducing methane emissions, but this still fails to increase yields. Thus, more research is needed to investigate synthetic fertilizers (their types and levels) and the ways in which they interact with other components, such as the water regime. Consequently, the significant effects on GHG emissions and crop yields will be better understood. A pot experiment conducted by Song et al. (2021), which combined AWD and phosphorus (P) fertilizer, resulted in an increased of grain yield (without reducing grain quality), decreased irrigation water use, and decreased irrigation events. Furthermore, this improved water-use efficiency (WUE) and partial factor productivity of applied P (PFPp). AWD irrigation increased the grain yield, mainly due to increased spikelets per plant and filled grains. The number of irrigation events was also reduced with AWD, which led to reduced water use. Yagi et al. (2019) analysed potential technical mitigation options in Southeast Asia, concluding that the application of biochar reduced both CH_4 and N_2O emissions by 20% (40%−−7%), while significantly increasing the rice yield by 28% (8%–52%). Initial research in China into combining AWD and zeolite suggests increased in N uptake, rice grain yield, economic benefit, and water productivity (Sun et al., 2019).

Although organic amendments could increase yields, they could also simultaneously increase emissions, especially when adding fresh rice straw. However, there is also evidence that decomposed fresh straw or compost could also decrease emissions. However, this finding requires further investigation. Research into low-methane varieties of rice remains a major topic for investigation, even in other countries. Thus, research should be conducted that involves breeders and a wider framework, as this would constitute a multidisciplinary consortium. This will be expensive work, but it will ultimately be worthwhile. Mitigation using specific low-emission rice varieties will be cost-effective because production costs and transactional costs will be lower, compared to water-management practices. A study by Song et al. (2020) asserts that different types of rice (lowland and upland) react differently to AWD's application, based on their dry root weight and root-oxidation activities. This study analysed differences in the transcriptome profiles of these rice varieties' roots. Similarly, Gutierrez et al. (2013) assessed eight Japonica cultivars' effect on CH_4 emissions and productivity in typical mono-rice paddy soil in Korea. These authors concluded that CH_4 fluxes do not correlate with apparent plant-growth parameters, yet they are highly correlated with methanogens and methanotrophs. This suggests that CH_4 emissions may be directly affected by each cultivar's substrate-producing potential and gas-transport capacity, rather than by external plant-growth variables (e.g., cultivar growing period). This result opposes research by Bhattacharyya et al. (2019), whose study concludes that a short-duration cultivar emits less CH_4 than a long-duration cultivar. In this study, CH_4 emission rates were lowest in short-duration cultivars, followed by medium cultivars and long-duration cultivars. The rate of CH_4 emission was mainly controlled by aerenchyma orientation, root exudation, and biomass production rate, all of which are key specific traits of a cultivar.

Anthropogenic activities that elevate soil-trace emissions play an important role in the atmospheric balance of the trace gas. GHG emissions from rice fields comprise a complex set of interactions between climatic conditions, soil properties, and management practices. The soil is a correction factor, which is used in IPCC emission calculations. Research has proven that different soil types have different potentials for GHG production, depending on several factors. Setyanto et al. (2002) and Wihardjaka and Harsanti (2011) have stated that specific soil types' potential production differs between the origin and those with added substrate. Thus, management practices play an important role. Meta-analysis by Shakoor et al. (2021) similarly emphasizes the ways in which agricultural management practices (e.g., fertilization, amendments to organic matter) affect CO_2, CH_4, and N_2O emissions. This study asserts that emissions were considerably dependent on soil attributes, such as soil pH, water-filled pore space (WFPS), soil texture, crop types, and climate zones. The most important factors to predict accurate GHG emissions were soil pH and soil texture.

Future research should focus on how management practices plays the role on specific soil types. Furthermore, there is a need for long-term research focusing on organic amendments and carbon sequestration from rice fields. Yagi et al. (2019) have stated that long-term observation (ideally for 20 years) is needed to accurately evaluate changes in SOC stocks in soil. There is also currently a dearth of information in the literature evaluating SOC stock changes, using long-term observations together with CH_4 and N_2O emissions from paddy fields in South East Asia. Tirol-Padre et al. (2018) and Cha-un et al. (2017) both assert that SOC stock changes do not significantly affect periods of AWD experiment on rice uplands and crop rotation, respectively. A study in Arkansas, the USA by Humphreys et al. (2019) evaluated the effects of SOM on CH_4 emissions from rice fields that were subjected to CF conditions across several silt-loam soils. The results showed that CH_4 emissions increased linearly ($P < 0.05$) as SOM and total carbon concentration increased (R2 = 0.81 and 0.85, respectively). In Korea, Shin et al. (2019) have shown that the use of biochar pellets (blended with animal manure compost) resulted in higher carbon sequestration in soil, compared to the control (animal manure compost only) after a rice-growing period.

This raises the question of how the combination of water regime, rice cultivar, fertilizer management, and soil type compares to each single effect, and how these factors will ultimately affect GHG emissions. When all these individual questions have been answered, robust data can be generated that determines country-specific emission factors that can model and calculate emissions. In their research in Bangladesh, Islam et al. (2018) found that combining the application of AWD and fertilization management (either deep fertilizer placement or using urea briquettes at lower rates than conventional broadcast fertilizer) can increase grain yields and nitrogen-use efficiency, which leads to lower N_2O emissions. An economical and social-scientific approach needs to be employed with regards to respected technologies because this will generate acceptable mitigation technologies for farmers. This mitigation technology will only be meaningful if it is accepted by the farmer, which relies on them obtaining economic profit despite the environmental benefits. As Ishfaq et al. (2020) also notes, an AWD system is both environmentally friendly and economically viable.

Measurements of CH_4 in Indonesia have mostly employed the manual chamber method. These chambers usually covered less than one square metre, and the manual chamber method is extremely limited in terms of sampling time and interval since this usually only includes 1–3 sampling times each day and mostly on a weekly or bi-weekly basis during a period of rice growth. Rice fields are relatively heterogeneous in terms of chemical and physical factors, water depth, SOC, and other biotic/abiotic factors. The small-scale coverage of CH_4 field measurements poses a challenge to upscaling the observed GHG flux. Therefore, continuous techniques would measure wide-scale GHG emissions more effectively. These techniques include eddy covariance (EC) observations, automated chambers, and satellite observation. Further research into crop-soil simulation models that are based on GIS should also be employed to assess GHG emissions from rice fields. Automated GHG efflux systems facilitate accurate measurements, minimal disturbance of the soil surface, and high-resolution datasets for extended periods of time (Pavelka et al., 2018). A study of rice fields in Japan, conducted at Tokyo University of Agriculture and Technology, compared two methods of closed chamber (CC) and EC. The study suggested that each method has different strengths and weaknesses, which can complement each other. Ultimately, using a combination of both methods enables better understanding of CH_4 emissions from paddy fields. Measurements using the CC method resulted in higher CH_4 flux averages than using EC (Chaichana et al., 2018). Li et al. (2020) used modified Moderate Resolution Imaging Spectrodiameter (MODIS) data to capture spatial patterns in rice paddies over several years accurately. The authors then designed an auto-thresholding and single vegetation index (normalized difference vegetation index [NDVI])-based procedure to estimate rice paddies' spatial distribution in China. This spatial pattern of rice paddies is an essential parameter that is now used to study GHG emissions, agricultural resource management, and environmental monitoring.

The proposed future framework for research and development

Currently, Indonesia's approach to climate change focuses more on adaptation than mitigation, and the primary focus is on farming practices that adapt to climate change and that have the secondary benefit of mitigating climate change. Adaptation actions that have a secondary benefit in terms of mitigation (by helping farmers improve farm productivity) sometimes incur higher advance costs. This can include labor and mechanization costs (Campbell et al., 2014). According to Smith et al. (2007), the implementation of mitigation technology faces several constraints and challenges. Most Indonesian farmers lack education because they live in villages that maintain strong cultural traditions. Cultivation techniques are mostly based on local knowledge, so farmers often experience difficulties obtaining new knowledge that is brought in from outside their community. Mitigation actions often introduce additional activities, both on and off the farm, which generate additional transactional costs. This makes farmers unwilling to practice these new activities. MacLeod et al. (2010) outline four adoption levels with regards to GHG-mitigation technologies:

Maximum technical: Farmers will willingly adopt a technology if they fully understand the necessary technical concept;

1. High feasibility: A form of mitigation technology may be adopted in the presence of government regulation;
2. Central feasibility: A form of mitigation technology will not be adopted unless a government subsidy is provided;
3. Low feasibility: The possibility of adopting the technology is extremely low if it is only accompanied by training and public schooling.

The development of agricultural adaptation and mitigation practices will require significant investment in technological innovation, which must be linked to increasingly efficient inputs and the creation of incentives and monitoring systems that actively include smallholder farmers (Vermeulen et al., 2012). Interdisciplinary approaches are needed to ensure researchers' and other stakeholders' needs are balanced with the longer-term global climate issue. This should align with global or national strategies to achieve synergy between research and adaptation mitigation practices (Suckal et al., 2015). This is summarized in Figure 4. A study by (Suarma et al. 2018) on the importance of participatory implementation within climate change-related policies in Indonesia revealed that the participatory method effectively evaluates climate change-related policies. Community participation from government, private sector, and local communities should be included in the program evaluation, to build a strong trust, effectiveness, and fairness of a program that leads to a successful program or policy.

As a non-annex I party, Indonesia is obliged to report its GHG emissions status to the UNFCCC every four years and its current mitigation achievement every two years. These reports require robust data from scientific research, which is then developed and tested multi-locally to ensure the emissions calculations are accurate. This is the first requirement for scientific research of GHG emissions in agriculture, and the second is that research should focus on providing farmers with simple, cost-effective, and sustainable farming techniques. To develop effective GHG mitigation strategies, future research should quantify the global warming potential (accounting for both CH_4 and N_2O emissions) and GHG intensity (per yield produced), investigate potential combinations of mitigation practices (e.g., water management and organic amendment), determine the social requirements and economic feasibility of these practices, facilitate technical assistance, and set up an institutional arrangement for monitoring. These pivotal aspects are presented in Figure 4, which outlines a future framework for GHG research and development. Following these steps and publishing all results in peer-reviewed publications will provide robust data about GHG emissions in rice fields.

Conclusion

Robust data concerning rice cultivation and GHG emissions in Indonesia has not been published in peer-reviewed periodicals, which has resulted in a lack of scientific information regarding this global issue. The research should provide a reliable, accurate, and robust dataset regarding GHG emissions from field measurements, which has ultimately identified the need for country-specific emission factors and also provide farmers with simple, cost-effective, and sustainable farming techniques. Existing gaps in research exploring GHG emissions from rice fields have also been presented in this study. More research regarding this issue in Indonesia is needed to obtain more robust scientific evidence about controlling factors for GHG emissions in rice fields. This evidence and data can inform national emission estimations and influence future mitigation measures. Based on this review, rice-production systems' soil types and management practices play critical roles in GHG emissions. This review has also outlined a variety of factors, such as fertilizer application, water-management practices, crop variety, and soil type, all of which influence the level of GHG

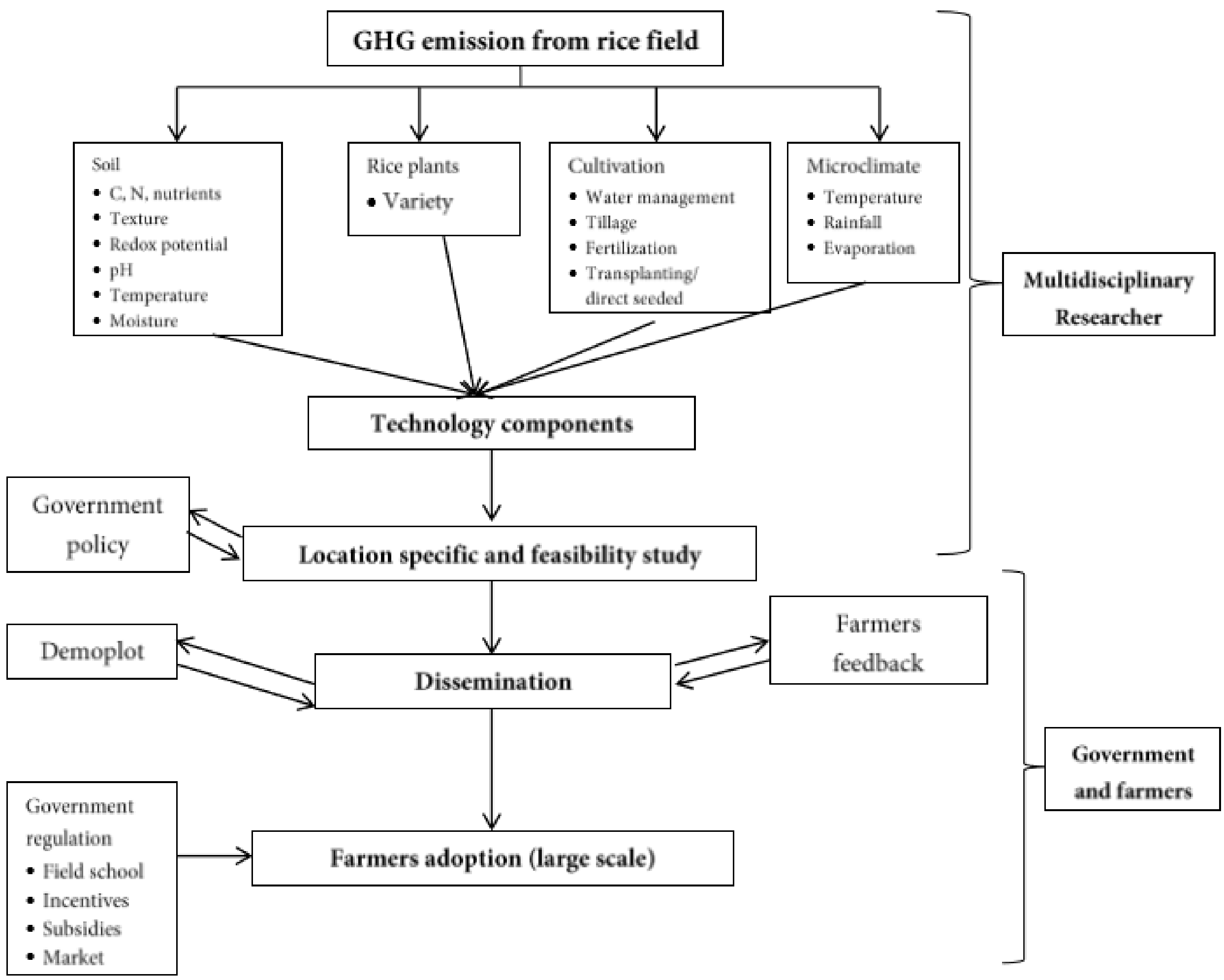

Figure 4. Framework for future agricultural research and development on mitigation and adaptation technology

emissions from rice fields worldwide. However, more evidence from Indonesia is needed. Several studies have been conducted, but these have mostly been plot experiments, so more research is needed to enhance understanding of wide-ranging farming fields. Economic benefits and social aspects must be addressed to fulfil national commitments. In conclusion, research exploring sustainable rice cultivation, particularly GHG emissions, should be conducted using a wider framework and a multidisciplinary approach that focuses on scientific evidence. This will help develop strong strategies in the development.

References

Adhya, T.K., Bharati, K., Mohanty, S.R., Ramakrishnan, B., Rao, V.R., Sethunathan, N. & R. Wassmann, (2000). Methane emission from rice fields at Cuttack, India. Nutrient Cycling in Agroecosystems 58: 95-105.

Adviento-Borbe, M. A. A., & B, Linquist, (2016). Assessing fertilizer N placement on CH_4 and N_2O emissions in irrigated rice systems. Geoderma, *266*, 40–45. https://doi.org/10.1016/j.geoderma.2015.11.034

Ali, M.A., Lee, C.H., & P.J. Kim, (2008). Effect of silicate fertilizer on reducing methane emission during rice cultivation. Biology and Fertility of Soils, 44, 597-604. doi:10.1007/s00374-007-0243-5\

Ariani, M., Kartikawati, R., & P. Setyanto, (2017). GHG emission and rice yield due to organic matter amendment on a poor rainfed rice field. 13th *International Conference of ESAFS proceedings* pp 95-104

Ball, B. C., Smith, K. A., Klemedtsson, L., Brumme, R., Sitaula, B. K., Hansen, S., & G. W. Horgan, (1997). The influence of soil gas transport properties on methane oxidation in a selection of northern European soils. Journal of Geophysical Research: Atmospheres, 102(D19), 23309–23317. https://doi.org/10.1029/97JD01663

Baruah, K. K., Gogoi, B., Gogoi, P., & P. K. Gupta, (2010). N_2O emission in relation to plant and soil properties and yield of rice varieties. Agronomy for Sustainable Development. 30:733-742.

Batjes, N.H., (1996). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science 47, 151–163

Bhattacharyya, P., Dash, P. K., Swain, C. K., Padhy, S. R., Roy, K. S., Neogi, S., & T. Mohapatra, (2019). Mechanism of plant mediated methane emission in tropical lowland rice. Science of the Total Environment, *651*, 84–92. https://doi.org/10.1016/j.scitotenv.2018.09.141

Bouwman, A. F., (1991). Agronomic aspects of wetland rice cultivation and associated methane emissions. Biogeochemistry, 15(2), 65-88. doi:10.1007/BF00003218

Bouwman, A. F., Boumans, L. J. M., & N. H. Batjes, (2002). Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochemical Cycles, 16(4), 6-1.

Brye, K. R., Rogers, C. W., Smartt, A. D., Norman, R. J., Hardke, J. T., & E. E. Gbur, (2017). Methane emissions as affected by crop rotation and rice cultivar in the Lower Mississippi River Valley, USA. Geoderma Regional, *11*(June), 8–17. https://doi.org/10.1016/j.geodrs.2017.08.004

Butterbach-Bahl, K., Papen, H., & H. Rennenberg, (1997). Impact of gas transport through rice cultivars on methane emission from paddy fields. Plant Cell Environment 20, 1175–1183

Butterbach-bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., & S. Zechmeister-boltenstern, (2013). Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Author for correspondence: Phil Trans R Soc *B*, 368 (The global nitrogen cycle in the twenty-first century), 1–20. https://doi.org/20130122

Butler, J. H., & S. A. Montzka, (2020). The NOAA annual greenhouse gas index (AGGI). NOAA Earth System Research Laboratory, USA. esrl.noaa.gov/gmd/aggi.aggi.html

Campbell, B., Chen, L., Dygert, C., & W. Dick, (2014). Tillage and crop rotation impacts on greenhouse gas fluxes from soil at two long-term agronomic experimental sites in Ohio. Journal of Soil and Water Conservation, 69(6), 543–552. https://doi.org/10.2489/jswc.69.6.543

Carrijo, D. R., Lundy, M. E., & B. A. Linquist, (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. Field Crops Research, 203, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002

Cha-un, N., Chidthaisong, A., Yagi, K., Sudo, S., & S. Towprayoon, (2017). Greenhouse gas emissions, soil carbon sequestration and crop yields in a rain-fed rice field with crop rotation management. Agriculture, Ecosystems and Environment, 237, 109–120. https://doi.org/10.1016/j.agee.2016.12.025

Chaichana, N., Bellingrath-kimura, S. D., & S. Komiya, (2018). Comparison of closed chamber and Eddy Covariance methods to improve the understanding of methane fluxes from rice paddy fields in Japan. Atmosphere, 9(356). https://doi.org/10.3390/atmos9090356

Chunmei, X., Liping, C., Song, C., Guang, C., Xiufu, Z., & W. Danying, (2018). Effects of soil microbes on methane emissions from paddy fields under varying soil oxygen conditions. Agronomy Journal, 110(5), 1738. https://doi.org/10.2134/agronj2017.12.0747

Cicerone, R. J., & R. S. Oremland, (1988). Biogeochemical aspects of atmospheric methane. Global Biogeochemical Cycles, *2*(4), 299-327. doi:10.1029/GB002i004p00299

Cicerone, R.J., Delwiche, C.C., Tyler, S.C., & P.R. Zimmerman, (1992). Methane emissions from California rice paddies with varied treatments. Global Biogeochemical Cycles 6, 233–248.

Dannenberg, S. & R. Conrad, (1999). Effect of rice plants on methane production and rhizospheric metabolism in paddy soil. Biogeochemistry 45: 53. doi.org/10.1007/BF00992873

Denmead, O. T., Macdonald, B. C. T., Bryant, G., Naylor, T., Wilson, S., Griffith, D. W. T., & P. W. Moody, (2010). Emissions of methane and nitrous oxide from Australian sugarcane soils. Agricultural and Forest Meteorology, 150(6), 748–756. https://doi.org/10.1016/j.agrformet.2009.06.018

FAO [Food and Agricultural Organization of the United Nations], (2009). OECD-FAO Agricultural Outlook 2011–2030.

FAO, (2017). Agroforestry in rice-production landscapes in Southeast Asia: a practical manual. Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific World Agroforestry Centre (ICRAF)

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., & R. Van Dorland, , (2007). In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & H.L. Miller, (Eds.), 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Frenzel, P., Bosse, U., & P. H. Janssen, (1999). Rice roots and methanogenesis in a paddy soil: ferric iron as an alternative electron acceptor in the rooted soil. Soil Biology and Biochemistry 31:421-430.

Gutierrez, J., Yoon, S., & P. Joo, (2013). Effect of rice cultivar on CH_4 emissions and productivity in Korean paddy soil. Field Crops Research, 146, 16–24. https://doi.org/10.1016/j.fcr.2013.03.003

Gogoi, N., Baruah K. K., & P. K. Gupta, (2008). Selection of rice genotypes for lower methane emission. Agronomy for Sustainable Development, 28:181-186.

Hadi, A., Inubushi, K., & K. Yagi, (2010). Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. Paddy and Water Environment, *8*(4), 319–324. https://doi.org/10.1007/

s10333-010-0210-x

Haque, M. M., Kim, S. Y., Ali, M. A., & P. J. Kim, (2014). Contribution of greenhouse gas emissions during cropping and fallow seasons on total global warming potential in mono-rice paddy soils. Plant and Soil, 387(1–2), 251–264. https://doi.org/10.1007/s11104-014-2287-2

Huang, Y., Jiao, Y., Zong, L., Zheng, X., Sass, R. L., & F. M. Fisher, (2002). Quantitative dependence of methane emission on soil properties. Nutrient Cycling in Agroecosystems, 64(1-2), 157-167. doi:10.1023/A:102113233026

Humphreys, J., Brye, K. R., Rector, C., & E. E. Gbur, (2019). Methane emissions from rice across a soil organic matter gradient in Alfisols of Arkansas, USA. Geoderma Regional, 16, e00200. https://doi.org/10.1016/j.geodrs.2018.e00200

Husin, Y. A, (1994). Methane Flux from Indonesia Wetland Rice: The Effects of Water Management and Rice Variety (PhD Thesis) Bogor Agricultural University. (In Indonesian with english abstract).

Holzapfel-Pschorn, A., Conrad, R., & W. Seiler, (1986). Effects of vegetation on the emission of methane from submerged paddy soil. Plant Soil, 92, 223-233

Horwath, W. R., (2011). Greenhouse gas emissions from rice cropping systems. Understanding Greenhouse Gas Emissions From Agricultural Management, (3), 67–89. https://doi.org/10.1021/bk-2011-1072.ch005

IPCC, (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Ishfaq, M., Farooq, M., Zulfiqar, U., Hussain, S., Akbar, N., Nawaz, A., & S. Ahmad, (2020). Alternate wetting and drying: A water-saving and ecofriendly rice production system. Agricultural Water Management, 241(February), 106363. https://doi.org/10.1016/j.agwat.2020.106363

Islam, S. M. M., Kanta, Y., Chandra, J., Jahan, S., Singh, U., Kumar, S., … & M. A. Saleque, (2018). Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: Fate of nitrogen and grain yield. Agricultural Water Management, *196*, 144–153. https://doi.org/10.1016/j.agwat.2017.11.002

Jain, N., Pathak, H., Mitra, S., & A. Bhatia, (2004). Emission of methane from rice fields - A review. Journal of Scientific and Industrial Research, 63(2), 101–115.

Janz, B., Weller, S., Kraus, D., Racela, H. S., Wassmann, R., Butterbach-Bahl, K., & R. Kiese, (2019). Greenhouse gas footprint of diversifying rice cropping systems: Impacts of water regime and organic amendments. Agriculture, Ecosystems and Environment, 270–271(October 2018), 41–54. https://doi.org/10.1016/j.agee.2018.10.011

Lal, R., (2004). Soil carbon sequestration impacts on global climate change and food security. Science (80-.) 304, 1623–1627. https://doi.org/10.1126/science.1097396.

Lal, R., (2003): Global potential of soil carbon sequestration to mitigate the greenhouse effect. CRC Crit. Rev. Plant Sci. 22, 151–184. https://doi.org/10.1080/713610854.

Le Mer, J.& P. Roger, (2001). Production, oxidation, emission and consumption of methane by soils: a review. European Journal of Soil Biology, 37: 25–50.

Li, B., Ti, C., & X. Yan, (2020). Estimating rice paddy areas in China using multi-temporal cloud-free normalized difference vegetation index (NDVI) imagery based on change detection. Pedosphere: An International Journal, *30*(6), 734–746. https://doi.org/10.1016/S1002-0160(17)60405-3

Lindau, C. W., Bollich, P. K., Delaune, R. D., Patrick, W. H., & V. J. Law, (1991). Effect of Urea Fertilizer and Environmental Factors on CH4 Emissions from a Louisiana, USA Rice Field. Plant Soil, 136 (2), 195–203. https://doi.org/10.1007/BF02150050.

Lindau, C.W., (1994). Methane emissions from Louisiana rice fields amended with nitrogen fertilizers. Soil Biol. Biochem. 26, 353–359.

Linquist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., & K. J. van Groenigen, (2012). Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. Field Crops Research, 135, 10-21. Elsevier B.V. https://doi.org/10.1016/j.fcr.2012.06.007

Lumbanraja, J., Ghani Nugroho, S., Suprapto, H., Sunyoto, Ardjasa, W. S., Kimura, M., & M. Kimura, (1997). Methane emission from an indonesian rainfed paddy field. Soil Science and Plant Nutrition, *43*(2), 479–482. https://doi.org/10.1080/00380768.1997.10414774

Luo, G.J., Kiese, R., Wolf, B., & K. Butterbach-Bahl, (2013). Effects of soil temperature and moisture on methane uptake and nitrous oxide emissions across three different ecosystem types. Biogeosciences 10: 3205–3219

Ma, K., Qiu, Q. F., & Y. H. Lu, (2010). Microbial mechanism for rice variety control on methane emission from rice field soil. Global Change Biology 16:3085-3095

MacLeod, M., Moran, D., Eory, V., Rees, R. M., Barnes, A., Topp, C. F. E., & A. Moxey, (2010). Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agricultural Systems, *103*(4), 198–209. https://doi.org/10.1016/j.agsy.2010.01.002

Minami, K., (1995). The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice. Fertil Res 40: 71–84.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., & L. Winowiecki, (2017). Soil carbon 4 per mille. Geoderma, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Mitra, S., Wassmann, R., Jain, M. C., & H. Pathak, (2002). Properties of rice soils affecting methane production potentials: 2. Differences in topsoil and subsoil. Nutrient Cycling in Agroecosystems, *64*(1–2), 183–191. https://doi.org/10.1023/A:1021175404418

MOA, (2016). Agricultural Statistics. Ministry of Agriculture, Government of Indonesia

MoEF, (2017). Indonesia's Third National Communication to the UNFCCC. Ministry of Environment and Forests, Government of Indonesia.

Neubauer, S.C., Toledo-Duran, G.E., & D. Emerson, (2007). Returning to their roots: iron-oxidizing bacteria enhance short-term plaque formation in the wetland-plant rhizosphere. Geomicrobiol J, 24: 65–73.

Neue, H.U., & R.L. Sass, (1994). Trace gas emission from rice fields. Environmental of Science Research 48: 119 – 147.

Nouchi, I., Mariko, S., & K. Aoki, (1990). Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. Plant Physiology 94:59-66.

Nouchi I., & S. Mariko, (1993). Mechanism of methane transport by rice plants. In: Oremland R.S. (eds) Biogeochemistry of Global Change, 336-352. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-2812-8_18

Nugroho, S. G., Lumbanraja, J., Suprapto, H., Sunyata, Ardjasa, W. S., Haraguchi, H., & M. Kimura, (1994). Methane emission from an indonesian paddy field subjected to several fertilizer treatments. Soil Science and Plant Nutrition, *40*(2), 275–281. https://doi.org/10.1080/00380768.1994.10413301

Nugroho, S. G., Sunyoto, S., Lumbanraja, J., Suprapto, H., Ardjasa, W. S., & M. Kimura, (1997). Effect of rice variety on methane emission from an indonesian paddy field. Soil Science and Plant Nutrition, 43(4), 799–809. https://doi.org/10.1080/00380768.1997.10414646

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & S. Erasmi, (2016). Greenhouse gas emissions from soils—A review. Chemie Der Erde - Geochemistry, *76*(3), 327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Oo, A. Z., Sudo, S., Inubushi, K., Chellappan, U., Yamamoto, A., Ono, K., & R. Venkatachalam, (2018). Mitigation potential and yield-scaled global warming potential of early-season drainage from a rice paddy in Tamil Nadu, India. Agronomy 2018, *8*(10), 202. https://doi.org/10.3390/AGRONOMY8100202

Pathak, H., Li, C., & R. Wassman,(2005): Grenhouse gas emissions from Indian Rice fields: calibration and upscaling using the DNDC model. Biogeosciences, 2: 113-123.

Pavelka, M., Acosta, M., Kiese, R., Altimir, N., Brümmer, C., Crill, P., … & A. Lohila, (2018). Standardisation of chamber technique for CO_2, N_2O and CH_4 fluxes measurements from terrestrial ecosystems. International Agrophysics, 32, 569–587. https://doi.org/10.1515/intag-2017-0045

Peyron, M., Bertora, C., Pelissetti, S., Said-Pullicino, D., Celi, L., Miniotti, E., & D. Sacco, (2016). Greenhouse gas emissions as affected by different water management practices in temperate rice paddies. Agriculture, Ecosystems and Environment, *232*, 17–28. https://doi.org/10.1016/j.agee.2016.07.021

Ro, S., Seanjan, P., & T. Tulaphitak, (2011). Sulfate content influencing methane production and emission from incubated soil and rice-planted soil in Northeast Thailand. Soil Science & Plant Nutrition, 57: 833–842

Sass, R. L., Fisher, F. M., Wang, Y. B., Turner, F. T., & M. F. Jund, (1992). Methane emission from rice fields: The effect of floodwater management. Global Biogeochemical Cycles, *6*(3), 249-262. doi:10.1029/92GB01674

Schutz, H., Holzapfel-Pschorrn, A., Conrad, R., Rennenberg, H., & W. Seiler, (1989). A3-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy. Journal of Geophysical Research 94, 16405–16416.

Setyanto, P., Makarim, A., Fauziah, C. I., & A. Bidin, (2002). Soil controlling factors of methane production from flooded rice fields in Pati district, Central Java. Indonesian Journal of Agricultural Science, *3*(1), 1–11. https://doi.org/10.21082/ijas.v3n1.2002.1-11

Setyanto, P., Makarim, A. K., Fagi, A. M., Wassmann, R., & L. V. Buendia, (2000). Crop management affecting methane emissions from irrigated and rainfed rice in Central Java (Indonesia). Nutrient Cycling in Agroecosystems, *58*(1–3), 85–93. https://doi.org/10.1023/A:1009834300790

Setyanto, P., & R. Kartikawati, (2011). Integrated rice crop management for low emittance of methane. Indonesian Jornal of Agriculture Science, 4 (1), 8-16.

Setyanto, P., Pramono, A., Adriany, T. A., Susilawati, H. L., Tokida, T., Padre, A. T., & K. Minamikawa, (2018). Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. Soil Science and Plant Nutrition, *64*(1), 23–30. https://doi.org/10.1080/00380768.2017.1409600

Shakoor, A., Shakoor, S., Rehman, A., Ashraf, F., Abdullah, M., Muhammad, S., … & M. Ahsan, (2021). Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils d A global meta- analysis. Journal of Cleaner Production, *278*, 124019. https://doi.org/10.1016/j.jclepro.2020.124019

Shin, J., Jang, E., Park, S., Ravindran, B., & Woong, S. (2019). Agro-environmental impacts , carbon sequestration and pro fi t analysis of blended biochar pellet application in the paddy soil-water system. Journal of Environmental Management, *244* (August 2018), 92–98. https://doi.org/10.1016/j.jenvman.2019.04.099

Signor, D., & C. E. P. Cerri, (2013). Nitrous oxide emissions in agricultural soils: a review. Pesquisa Agropecuária Tropical, *43* (3), 322–338. https://doi.org/10.1590/S1983-40632013000300014

Smartt, A. D., Brye, K. R., & R. J. Norman, (2016). Methane emissions from rice production in the United States — A Review of controlling factors and summary of research. In Intech open (Vol. 2, p. 64). https://doi.org/10.5772/32009

Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N.H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello, 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change (2014). Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Smith, K. A., Ball, T., Conen, F., Dobbie, K. E., Massheder, J., & A. Rey, (2018). Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. European Journal of Soil Science, 69(1), 10–20. https://doi.org/10.1111/ejss.12539

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., & S.Towprayoon, (2007).Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems and Environment, 118, 6-28. https://doi.org/10.1016/j.agee.2006.06.006

Song, T., Das, D., Hu, Q., Yang, F., & J. Zhang, (2021). Alternate wetting and drying irrigation and phosphorus rates affect grain yield and quality and heavy metal accumulation in rice. Science of the Total Environment, *752*, 141862. https://doi.org/10.1016/j.scitotenv.2020.141862

Song, T., Das, D., Yang, F., Chen, M., Tian, Y., & C. Cheng, (2020). Genome-wide transcriptome analysis of roots in two rice varieties in response to alternate wetting and drying irrigation. The Crop Journal, *8*(4), 586–601. https://doi.org/10.1016/j.cj.2020.01.007

Suarma, U., Hizbaron, D. R., S, S., & E. Nurjani, (2018). Participatory Implementation within Climate Change Related Policies in Urbanized Area of Indonesia. *Indomesian Journal of Geography*, *50*(2), 121–132. https://doi.org/http://dx.doi.org/10.22146/ijg.36262

Subadiyasa, N., Arya, N., & M. Kimura, (1997). Methane emissions from paddy fields in bali island, indonesia. Soil Science and Plant Nutrition, *43*(2), 387–394. https://doi.org/10.1080/00380768.1997.10414762

Suckall, N., Stringer, L. C., & E. L. Tompkins, (2015). Presenting Triple-Wins ? Assessing Projects That Deliver Adaptation , Mitigation and Development Co-Benefits in Rural Sub-Saharan Africa. *AMBIO*, 34–41. https://doi.org/10.1007/s13280-014-0520-0.

Sun, Y., Xia, G., He, Z., Wu, Q., Zheng, J., Li, Y., … & D. Chi, (2019). Zeolite amendment coupled with alternate wetting and drying to reduce nitrogen loss and enhance rice production. Field Crops Research, *235*(March), 95–103. https://doi.org/10.1016/j.fcr.2019.03.004

Susilawati, H. L., Setyanto, P., Makarim, A. K., Ariani, M., Ito, K., & K. Inubushi, (2015). Effects of steel slag applications on CH_4, N_2O and the yields of Indonesian rice fields: a case study during two consecutive rice-growing seasons at two sites. Soil Science and Plant Nutrition, 61(4), 704–718. https://doi.org/10.1080/00380768.2015.1041861

Tirol-Padre, A., K. Minamikawa, T. Tokida, R. Wassmann, & K. Yagi, (2018). Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: A Synthesis. Soil Science and Plant Nutrition 64: 2–13. doi:10.1080/ 00380768.2017.1409602

Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R., & A. Kunhikrishnan, (2013). Role of organic amendment application on greenhouse gas emission from soil. Science of the Total Environment, 465(August 2014), 72–96. https://doi.org/10.1016/j.scitotenv.2013.01.031

Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., & P. Smith, (2013). The Faostat database of greenhouse gas emissions from agriculture. Environmental Research Letter 8, 1–11.

Vermeulen, S.J., Aggarwal, P.K., Ainslie, A., Angelone, C., Campbell, B.M., Challinor, A.J., Hansen, J.W., Ingram, J.S.I., Jarvis, A., Kristjanson, P., others., (2012). Options for support to agriculture and food security under climate change. Environmental Science and Policy 15, 136e144

Wang, Z.P., Lindau, C.W., Delaune, R.D., & W.H. Patrick Jr., (1993). Methane emission and entrapment in flooded rice soils as affected by soil properties. Biology and Fertility of Soils 16, 163–168. http://doi.org/10.1007/BF00361401.

Wang, B., Xu, Y., Wang, Z., Li, Z., Guo, Y., Shao, K., & Z. Chen, (1999). Methane emissions from ricefields as affected by organic amendment, water regime, crop establishment, and rice cultivar. Environ. Monit. Assess. 57, 213–228.Wang, C., Lai, D. Y. F., Sardans, J., Wang, W., Zeng, C., & J. Peñuelas, (2017). Factors related with CH_4 and N_2O emissions from a paddy field: Clues for management implications. PLoS ONE, 12(1), 1–23. https://doi.org/10.1371/journal.pone.0169254

Wang, J., H. Akiyama, K. Yagi, & X. Yan, (2018). Controlling Variables and Emission Factors of Methane from Global Rice Fields. Atmospheric Chemistry and Physics 18: 10419–10431. doi:10.5194/acp-18-10419-2018.

Watanabe, A., & M. Kimura, (1999). Influence of chemical properties of soils on methane emission from rice paddies. Communication Soil Science & Plant Analysis, 30, 2449–2463. 10.1080/00103629909370386

Wihardjaka, A., (2007). Methane emissions from sime rice cultivar in rainfed rice field. Jurnal Biologi Indonesia, 4 (3): 143-152. In Indonesian

Wihardjaka, A., (2010). Nitrous oxide emission from rainfed rice field amended with rice straw and nitrification inhibitor. Jurnal Biologi Indonesia, 6(2), 211–224. In Indonesian

Wihardjaka, A., & E. S. Harsanti, (2011). Methane production potential from several soil types in Central Java. Ecolab, 5 (November), 68–78. In Indonesian

Wihardjaka, A., & Poniman, (2015). Contribution of sulfur to rice productivity and atmospheric greenhouse gases in Lowland. Journal Pangan, 9–17. In Indonesian

Wihardjaka, & Sarwoto, (2015). Greenhouse gases emission and grain yield from several rice varieties in rainfed rice field, Central Java. Ecolab, 9(1), 9–16. In Indonesian

Xie, B., Zheng, X., Zhou, Z., Gu, J., Zhu, B., & X. Chen, (2009). Effects of nitrogen fertilizer on CH_4 emission from rice fields: multi-site field observations. Plant Soil 326, 393–401.

Yagi, K., & K. Minami, (1990). Effect of organic matter application on methane emission from some japanese paddy fields. Soil Science and Plant Nutrition, 36(4), 599-610. doi:10.1080/00380768.1990.10416797

Yagi, K., Sriphirom, P., Cha-un, N., Chidthaisong, A., & B. Damen, (2019). Potential and promisingness of technical options for mitigating greenhouse gas emissions from rice cultivation in Southeast Asian countries. Soil Science and Plant Nutrition, 00 (00), 1–13. https://doi.org/10.1080/00380768.2019.1683890

Yan, X., Du, L., Shi, S., & G. Xing, (2000). Nitrous oxide emission from wetland rice soil as affected by the application of controlled-availability fertilizers and mid-season aeration. Biol. Fertil. Soils., 32, 60-66.

Yan, X., Yagi, K., Akiyama, H., & H. Akimoto, (2005). Statistical analysis of themajor variables controllingmethane emission fromrice fields. Global Change Biology 11:1131-1141

Yang, S., & H. Chang, (2000). Effect of green manure amendment and flooding on methane emission from paddy fields. Chemosphere - Global Change Science, 3(1), 41-49. doi:10.1016/S1465-9972(00)00032-5

Yuan, J., Yuan, Y., Zhu, Y., & L. Cao, (2018). Effects of different fertilizers on methane emissions and methanogenic community structures in paddy rhizosphere soil. Science of the Total Environment, 627, 770–781. https://doi.org/10.1016/j.scitotenv.2018.01.233

Zhao, X., Pu, C., Ma, S. T., Liu, S. L., Xue, J. F., Wang, X., & H. L. Zhang, (2019). Management-induced greenhouse gases emission mitigation in global rice production. Science of the Total Environment, 649, 1299–1306. https://doi.org/10.1016/j.scitotenv.2018.08.392