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Assessing N_2O Emissions from Tropical Crop Cultivation in Mineral and Peatland Soils: A Review

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Abstract

Nitrous oxide (N_2O) emissions from agricultural activities contribute significantly to global warming. Understanding the factors influencing N_2O emissions is crucial for developing effective mitigation strategies. This review assesses N_2O emissions from various crops cultivated in tropical mineral and peatland soils, providing insights into the impact of land use, fertilization practices and rainfall on N_2O fluxes. Field measurements of N_2O fluxes were conducted in agricultural fields growing corn, peanuts, and cassava in Bogor Regency, West Java Province, as well as in peatland areas with Acacia plantations and natural primary forests in Bengkalis Regency, Riau Province. The study assesses the total N_2O fluxes for each crop and land type, revealing significant variations in N_2O emissions among different crops and land uses. Peatland areas exhibit higher emissions compared to mineral soils, emphasizing the need for targeted mitigation measures in these ecosystems. The findings highlight the importance of considering the type and age of land use when evaluating N_2O emissions. Land management practices, such as fertilizer use and soil disturbance, emerge as critical factors affecting N_2O emissions. Improper fertilizer application and excessive soil disturbance can lead to increased N_2O emissions, underscoring the necessity for careful N fertilizer management and conservation tillage techniques.

Keywords: agricultural land; closed chamber method; N_2O gas emission; peatland soil; tropical mineral soil

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INTRODUCTION

Agricultural activities are widely known to heavily influence the emission of greenhouse gases (GHGs) namely CO_2, CH_4 and N_2O into the atmosphere (Kweku et al., 2018). Plant activity can increase CO_2 emission from soil (Yerli et al., 2022). Although CO_2 is by far the most abundant GHG, N_2O is also important because of its unique radiative properties and long residence time in the atmosphere (Hodnebrog et al., 2020). N_2O molecules remain in the atmosphere for around 114 years before being extracted through a chemical reaction. It is a different N_2O lifespan than CO_2; molecules of CO_2 hang in the atmosphere for around 5 to 200 years. Nevertheless, no single lifespan can be expounded for CO_2 because of the different rates of removal processes (IPCC, 2022a). N_2O is also resulting in a global warming potential (GWP) of around 296 times that of CO_2 (Hodnebrog et al., 2020). Specifically, one pound of N_2O in the atmosphere is 296 times that of one pound of CO_2. In line with this, it was also stated that N_2O has a shorter

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atmospheric lifetime of approximately 110 years compared to CO_2, which has a lifetime of around 120 years (Ritchie et al., 2020). The impact of this GHG is defined as "the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of the reference gas, CO_2" (Hsiao, 2022).

According to the latest information from the Intergovernmental Panel on Climate Change (IPCC), N_2O is a GHG with a global warming potential nearly 310 times that of CO_2 within 100 years (IPCC, 2022b). N_2O has a GWP of 273 times that of CO_2 for a 100-year timescale and a lifetime of 110 to 132 years (Prather et al., 2015). The global concentration of N_2O has increased from 270 ppb to 319 ppb in the last decade, with approximately 80% of the world's total N_2O emissions related to agricultural activities (IPCC, 2023).

In recent years, GWP has been used to evaluate the effect of agricultural activities on global warming (Costa et al., 2021). Nugroho et al. (2018) stated that the difference in soil properties such as soil texture, drainage, water-filled pore space (WFPS), and C/N ratio probably cause the magnitude of CO_2 emission. CO_2 flux is affected by environmental factors such as temperature, moisture content and humidity of the soil, as well as the type and extent of vegetation cover (Hendri et al., 2015; Busman et al., 2023). It is essential to understand the factors that contribute to N_2O emissions from different crops and soil types to develop effective strategies for mitigating N_2O emissions. The identification of crops and soil types that produce lower levels of N_2O can help to reduce the impact of agricultural activities on the environment. Moreover, it is crucial to identify management practices that can help to reduce N_2O emissions from crops grown in tropical mineral and peatland soil. The factors that may influence N_2O emission include soil type and management characteristics (Soares et al., 2023).

Mineral and peatland soil in Indonesia mostly is utilized for agricultural cultivation (Gunawan, 2018; Uda et al., 2020; Ahmad, 2021). Therefore, the various agricultural activities in both mineral and peatland soil can contribute to N_2O emissions. In mineral soil, common agricultural activities include the use of synthetic fertilizers, tillage and irrigation, which can all increase N_2O emissions (C. Wang et al., 2021; Hassan et al., 2022). In contrast, in peatland soil, agricultural activities such as drainage and land conversion can significantly increase N_2O emissions (Buschmann et al., 2020). Excessive drainage of peatlands can create large negative impacts on the climate in the tropical regions. In addition, drainage (groundwater level ≥ 0.5 m) caused a larger than 60 times increase in N_2O than under shallow groundwater conditions (Prananto et al., 2020). Drainage reduces soil water content and leads to an increase in O_2 availability, which can stimulate N_2O producing microbial activity (C. Wang et al., 2021). Land conversion from natural peatland forests to agricultural land can also increase N_2O emissions due to changes in soil physical and chemical properties, as well as changes in microbial communities (Arai et al., 2014; Dhandapani et al., 2023).

Given the above premise, the key objective of this study was to estimate the total flux of N_2O from tropical land with mineral soil that is planted to corn, peanut and cassava crops. In addition, it also determines the total N_2O flux from tropical soil with peatlands planted with *Acacia crassicarpa* and primary forests of various ages. N_2O emission can be mitigated appropriately if the causal factors can be identified accurately, especially in the agricultural sector. Thus, this review article discusses the mechanism of N_2O formation and factors that cause N_2O emissions from various agricultural cultivation and soil types. At the same time, recognizing the factors that affect the flux of N_2O from agricultural land, this study can be used as a preliminary study for developing practical methods to reduce N_2O emissions, while optimizing fertilizer efficiency at field study.

Sustainable agricultural practices are crucial for reducing the environmental impact of agricultural activities, especially in developing countries (Hassan et al., 2022). In support of sustainable agricultural systems, this review highlights the significance of understanding the mechanisms of N_2O formation and the factors contributing to N_2O emissions in different agricultural and soil types. By identifying crops and soil management practices that lead to lower N_2O emissions, it becomes possible to reduce the environmental impact of agricultural activities. This knowledge is particularly valuable for developing countries, where agriculture plays a crucial role in their economies and environmental sustainability (Lawrence et al., 2021). By gaining a deeper understanding of the factors contributing to N_2O emissions, particularly in the context of tropical crop cultivation on mineral and peatland soils, stakeholders such as governments and farmers

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can develop informed strategies and policies for the application of chemical fertilizers and agricultural management. Hence, it will extremely support sustainable agriculture.

MATERIALS AND METHOD

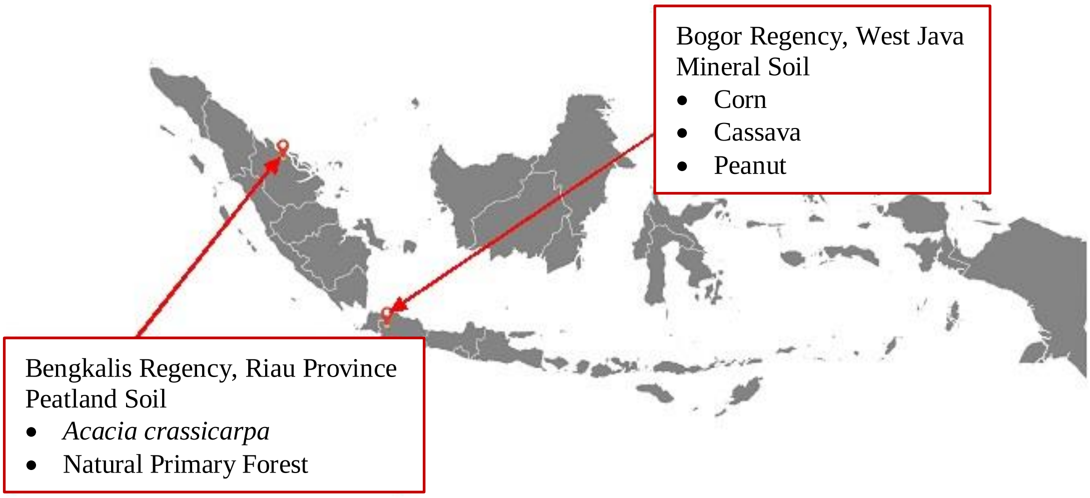
Through desk study, various in-depth sources such as government reports from 2015 to 2023, peer-reviewed papers and other supporting data were particularly collected to complete this review article. Researchers methodically searched peer-reviewed papers that were published from 2020 until 2023 with the following keywords: “nitrous oxide” or N_2O”, “legume”, “peanut”, “cassava”, “maize”, “tropical soil” and “peatland soil”. To obtain credible data on N_2O flux patterns, the following further criteria were adopted: only annually measured in situ fluxes were included and the samples were collected using the closed Chamber method.

This paper also integrated the review with primary data to get accurate data. For mineral soil, the field experiment was conducted in an agricultural field where corn (*Zea mays*), peanut (*Arachis hypogaea*), and cassava (*Manihot esculenta*) have been cultivated on a rotation basis for several decades. The field was located in Bantar Kambing Village, Bogor Regency, West Java Province, Indonesia (106°43’38.42” E, 6°32’12.36” S) (Figure 1). In this study, all crops were planted in November 2010. The growing period (from planting to harvesting) for corn and peanuts is about 2 to 3 months, but cassava requires a much longer growing period, which is around 7 to 9 months. Hence, the site observations were done at three different ages for the cassava field: 0 to 3 months, 3 to 6 months, and 6 to 9 months, whereas for corn and peanut, measurements were undertaken for each growing period. Moreover, to determine the flux of N_2O it was necessary to secure similar environmental conditions, particularly microclimatic conditions (e.g., weather, rainfall). This study fell under the November 2010 to February 2011 growing season. The micro-climatic description of the site can be summarized as follows: mean annual precipitation 2,500 to 5,000 mm year^{-1}, mean annual temperature 20 to 30 °C. The soil is classified as *Aquic dystrudept* with clay textural class.

The peatland soil field experiment was conducted in Bukit Batu Hutani Alam Company (BBHA), Bengkalis Regency, Riau Province, Indonesia (101°47’42.30” E, 1°29’10.52” N) (Figure 1). The land use type is natural primary forest, which since 2009 has been designated as a UNESCO’s Man and the Biosphere Programme (MAB) biosphere reserve and *A. crassicarpa* with different ages (1 and 3 years) and natural primary forest and *A. crassicarpa* 3 years R-L that means (without fine root and litter). The micro-climatic description of the site peatland can be summarized as: mean annual precipitation 809 to 4,078 mm year^{-1}, mean annual temperature 26 to 32 °C. The soil is classified as a deep peatland of more than 3 m and could be classified as fibric (Sumawinata et al., 2014).

Gas sampling and analysis

N_2O fluxes were measured every week from planting until harvesting in crop fields on mineral soils. Measurements of gas at each site were always conducted between 07:00 a.m. and



Bogor Regency, West Java
Mineral Soil
- Corn
- Cassava
- Peanut

Bengkalis Regency, Riau Province
Peatland Soil
- *Acacia crassicarpa*
- Natural Primary Forest

Figure 1. Location of the study sites in Riau and West Java Province

1:00 p.m. to minimize the diurnal variation in the flux pattern. Earlier studies had shown that diurnal N_2O production varies with diurnal soil temperature, which is at its lowest at sunrise (Reeves and Wang, 2015) and peaks in the late afternoon. The collection of gas N_2O samples was conducted monthly in peatland soil. Gas samples were collected during the daytime (from about 09:00 a.m. to almost 06:00 p.m.) when the site vegetation was likely to be most physiologically active.

Gas samples were collected using the Closed Chamber Method. The 30 cm x 30 cm x 30 cm chambers were each made of acrylic material, lined with UV paper, and equipped with a fan and a thermometer. During measurement, the chamber was placed on a metal chamber base. The chamber base was planted in the sample plot and was left undisturbed during the sample collection period. In each measurement plot, three chambers were placed to serve as replication. Further, the chamber base was installed in such a way as to eliminate or minimize the effects of fine roots and litter (treatment: -R-L).

The scheme of gas sample collection and the apparatus used are illustrated in Figure 2. The collection of gas samples was conducted in a time-series pattern, that is, at 10-, 20-, and 30-minute intervals for determining N_2O. For N_2O determination, as much as 10 ml gas samples were infused into vial bottles, and subsequently analyzed using Gas Chromatography Shimadzu 14B with detector Electron Capture Detector to quantify N_2O in the laboratory at Hokkaido University, Japan. The environmental factors that affect the production and release of the gases in the field, such as air temperature, soil temperature, and air humidity, were also recorded (Sumawinata et al., 2014).

The N_2O flux was calculated as the difference between ambient concentration and the concentration in the closed chamber, assuming a linear relationship between concentration and time (Rapson and Dacres, 2014) which was occasionally checked during the experiment. The accumulated fluxes were calculated by linear interpolation between measurement days. Seasonal total amounts of N_2O emission were sequentially accumulated from the emissions between pairs of consecutive measurement intervals.

In addition to gas sampling, the environmental factor that affect N_2O flux such as air temperature, soil temperature, relative humidity, and soil samples for chemical and physical analysis were also recorded both mineral and peatland soil. Air temperature and relative humidity were measured using a thermo-hygrometer, while portable temperature probes were used to determine soil temperature at a depth of 5 cm. Soil samples were collected using a soil sampling ring.

RESULTS AND DISCUSSION

N_2O gasses formed

The emission of N_2O occurs naturally through many sources associated with the N cycle, which is the natural circulation of N between the atmosphere, plants, animals, and microorganisms

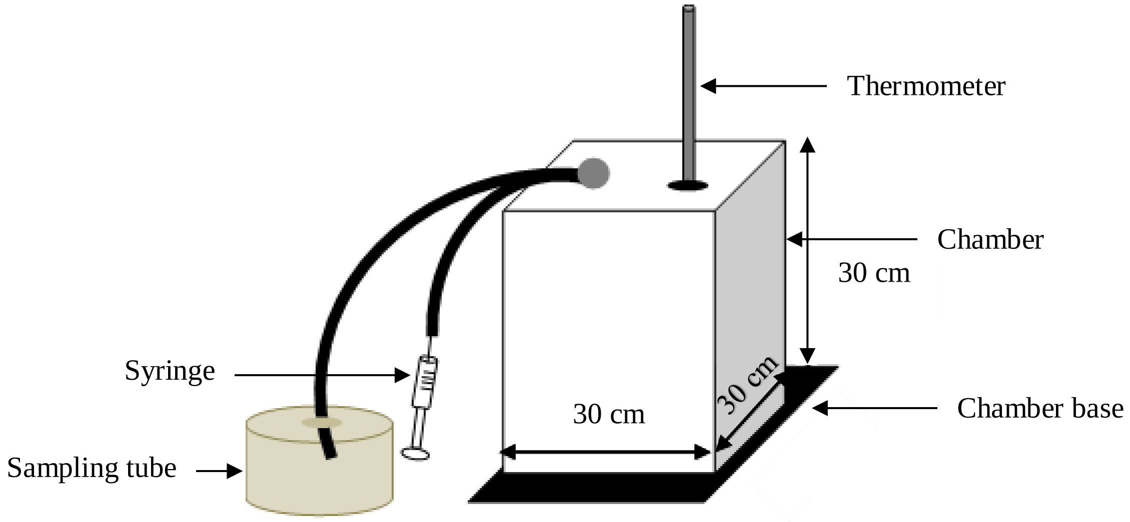


Figure 2. Measurement of N_2O flux using Closed Chamber Method

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that live in soil and water (Delgado and Follett, 2002; Harris et al., 2022). Nitrogen takes various chemical forms throughout the N cycle, including N_2O (Martínez-Espinosa et al., 2023). Natural emissions of N_2O comes primarily from bacteria that analyze N in the soil and oceans (Richards et al., 2016; Ito et al., 2018). Bacteria play an important role in the N_2 cycle in the atmosphere that also influence the formation of N_2O. Ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) lead autotrophic nitrification process. Nitrification initiates with a two-step process. At the first step, NH_3 is oxidized to NO_2^- by AOB, followed by the oxidation of NO_2^- to NO_3^- stimulated by NOB. The process was then followed by anaerobic denitrification stimulated by denitrifying bacteria (Rajta et al., 2020). Almost all N_2O is formed because of nitrification and denitrification processes in the soil (Figure 3).

N_2O production in the soil primarily occurs through microbial nitrification and denitrification processes. Nitrification involves the oxidation NH_4^+ to NO_2^- and further to NO_3^- by nitrifying bacteria. Denitrification, on the other hand, converts NO_3^- to N_2 under anaerobic conditions through a series of reduction steps, including the reduction of NO_3^- to NO_2^-, NO, and ultimately N_2O. N_2O can further be reduced to N_2 by denitrifying bacteria. Nitrification helps convert NH_3 into plant-available NO_3^-, while denitrification removes excess NO_3^- and releases N back into the atmosphere. Understanding these microbial processes is essential for managing and mitigating N_2O emissions in agricultural and natural ecosystems (Ghaly and Ramakrisnan, 2015).

Another microorganism involved in the nitrification and denitrification process is fungi, which can emit N_2 and N_2O by denitrification and codenitrification. On the other hand, Archaea stimulating nitrification in marine ecosystems can promote denitrification in soils (Lu et al., 2020). According to Zajac and Zubrowska-Sudol (2022), nitrification releases N_2O when O_2 is limited. Macdonald et al. (2016); Shaaban et al. (2018); and C. Wang et al. (2021) reported that N_2O emission will proportionately rise when pH and organic matter increase. Certainly, it happens when soil moisture also rises (from air dry to field capacity) around 5 to 40 °C. Nevertheless, N_2O emission can be lessened by applying nitrification inhibitors (Lam et al., 2017). Hence, the synthesis of N_2O is a complex process caused by numerous factors, such as pH, texture, soil moisture, soil temperature, organic matter, and abundance of O_2 (Macdonald et al., 2016; Wrage-Mönnig et al., 2018; C. Wang et al., 2021; Romero et al., 2021).

Around 40% of N_2O is formed from human activities such as agriculture, fuel combustion and industrial processes (Addington et al., 2021).

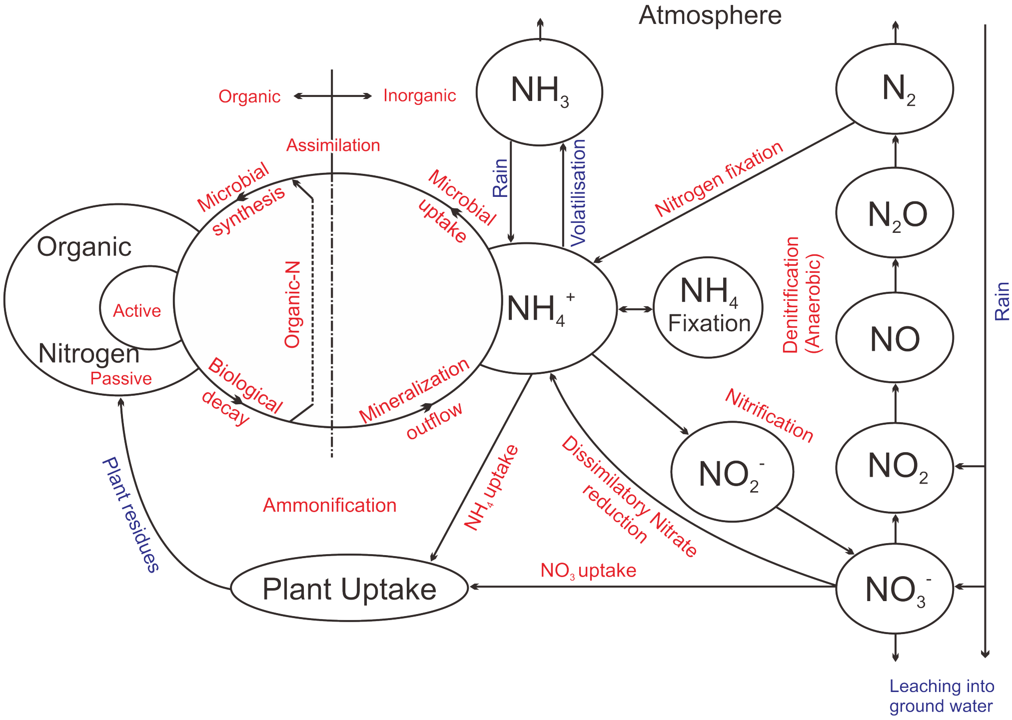

Figure 3. Nitrogen cycle (Ghaly and Ramakrisnan, 2015)

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The amount of N_2O emissions in Indonesia is presented in Table 1.

Table 1 provides an overview of the main sources of N_2O emissions in Indonesia for the years 2010, 2015 and 2020. Agriculture is identified as the largest contributor, primarily due to the use of N-based fertilizers and other agricultural practices. Fossil fuel combustion and industrial processes also contribute to N_2O emissions, albeit to a lesser extent. Land use change and forest activities emerge as significant sources, particularly in 2015, indicating the impact of deforestation and forest degradation. Waste management plays a relatively stable role in N_2O emissions.

Factors determining N_2O production in agriculture cultivation

As aforementioned that N_2O is formed during enzymatic nitrification and denitrification processes and chemo-denitrification (Stanton et al., 2018). N_2O emission is affected by the chemical and physical conditions of the soil, such as soil aeration, temperature, moisture, compaction, texture, pH, available N, C/N ratio, organic matter, and by soil management and crop rotation (Ashiq et al., 2021). Moreover, crop rotation, N sources, and fertilizing method (time and depth) also influence N_2O emission (Rychel et al., 2020).

Soil properties

The dynamic of N_2O emission not only influence by soil N availability but also soil properties such as pH, soil moisture, organic matter addition (Baruah et al., 2010). Zhu et al. (2021) reported that high soil moisture stimulates N_2O emission, but amount of N_2O flux is differences among different of soil type. Soil moisture has a great role in N_2O emission since it controls the O_2 supply to soil microbes (Butterbach-Bahl et al., 2013). Around 70% to 80% WFPS (depending on the soil type) is the optimum range for N_2O emission from soil, with the major final product is N_2 (denitrification process) (Davidson et al., 2000). In line with this statement, Butterbach-Bahl et al. (2013) reported that the optimum N_2O emission from soil was under wetter conditions than 80% WFPS. At higher soil moisture, the major end product of denitrification is N_2.

Beside soil moisture, it was found that temperature has a significant influence on denitrification process (Qu et al., 2022). Increasing temperature due to soil respiration leads to a depletion of soil oxygen concentrations and increases soil anaerobiosis. These activities also stimulate several temperature-sensitive microbial processes within the N cycle, and certain effect on N_2O emission (Butterbach-Bahl et al., 2013).

Zhu et al. (2021) reported that N_2O fluxes also increased following either manure application. Soil N_2O emissions were larger for urine than dung addition. Several macro-faunas such as termites are predicted to influence N_2O emission. It is possible that termites may transfer some organic matters from dung or manure away and effect on soil texture and pH. Clay particles hold water in soil aggregates. Furthermore, clay soils mostly have a low gas diffusivity due to small average pore sizes (Hu et al., 2018). In addition, high clay content normally ties in a high cation exchange capacity (CEC). As a consequence, the mineralized NH_4 ion can be adsorbed since the CEC is high or even fixed to the clay minerals (Chantigny et al., 2004), it takes an impact on decreasing soil NH_4 ion availability for nitrification and, thus, NO_3 ion production. Hence, the soil NH_4^+ sorption capacity has been found to affect N_2O production (Venterea et al., 2015).

N fertilizing

Even though NH_4^+ is used in the nitrification process and NO_3^- is used in the denitrification process, N_2O emission from agricultural fields

Table 1. Main sources of N_2O in the atmosphere in Indonesia

Source	Gg CO_2e		
	2010	2015	2020
Anthropic sources:			
Fossil fuel combustion	15.12	17.39	0.03
Industrial process and product use	0.30	5.00	3.72
Agriculture	152.26	157.29	171.09
Land use change and forestry	0.00	30.89	2.53
Other (waste)	9.27	9.96	11.91
Total anthropic sources	167.68	210.57	189.28

Source: Ministry of Environment and Forestry of Indonesia (2022)

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usually comes in proportion to the N application rate (Wrage-Mönnig et al., 2018). In addition, Roy et al. (2014) stated that the increase in N_2O emissions is directly proportional to the application rate of N fertilizer.

In conventional Indonesian agriculture, urea is an N fertilizer that is commonly used. Urea is subject to N losses from cultivated fields that include "denitrification", or the conversion of NO_3^- into N_2 (gas); leaching (the downward movement of NO_3^- out of the root zone); plant uptake and removal in harvested portions of the crop; and NH_3 volatilization (from soils and some plants). Two other reactions, "immobilization" (uptake by microorganisms) and "exchange" (binding of soil particles), are considered temporary "losses" because the N remains in the soil, and most of it becomes available (Menegat et al., 2022).

The application of N fertilizer increases the potential for N_2O production by providing a substrate. There is strong evidence that the form of N fertilizer, especially inorganic N, influences the production of N_2O (Xie et al., 2022). For instance, Chen et al. (2019) pointed out that N fertilizer above plant needs is more likely to result in N_2O flux. Similarly, Hassan et al. (2022) stated the importance of matching N application. N_2O flux is significantly increased using N fertilizers, especially when followed by rain (Suwardi et al., 2015). Due to rain, increasing groundwater levels can affect the denitrification process (Weymann et al., 2009; Jurado et al., 2017).

Soil tillage

Tillage practices have been widely known for affecting cropping systems, both conservation tillage practices such as no-tillage, reduced or minimum tillage, and conventional tillage (Lv et al., 2023). Generally, conservation tillage is related to water infiltration improvement, ameliorating soil structure, and reduced soil erosion (Rehman et al., 2023). Soil tillage practices also affect N_2O emissions due to the N_2 cycle in soil. The activity of *Nitrosomonas* sp. and *Nitrobacter* sp. that handle nitrification are determined by optimal soil temperature and moisture condition.

Abundant soil moisture and available organic carbon could support the complete reduction of low to moderate levels of NO_3 to N_2 gas, consequently reducing the net amount of N_2O produced (Senbayram et al., 2019). Furthermore, higher levels of NO_3 led to higher net N_2O:N_2 emission ratios, because the reduction of NO_3 in comparison with N_2O was more energy-efficient (Friedl et al., 2020). According to Huang et al. (2022), it seems that during the period of transition from conventional tillage to no-tillage, the N immobilization is accompanied by slow soil organic matter turnover. Alam et al. (2020) suggested that N availability for the crops was lower under no-tillage than under conventional tillage. Moreover, others found that the higher application rates of inorganic fertilizer can be beneficial to the N uptake of crop during the transition period from standard to minimum tillage to account for the lower N mineralization rates (Mondal and Chakraborty, 2022). Some studies showed that N_2O emission was greater in no-tilled soils than in conventionally tilled soils (Gregorich et al., 2008; Holder et al., 2019), but other studies reported that N_2O emission was greater in conventionally tilled soils than in no-tilled soils (Yoo et al., 2016; Sosulski et al., 2022).

Other factors

The results of researchers exploration on the factors that affect N_2O flux for both mineral soil and peatland showed that in corn fields, the average soil moisture was 46.4%, peanuts 36.9%, and cassava 43.4%. In peatland areas, the average soil moisture for *A. crassicarpa* at 1 year was 190.6% while *A. crassicarpa* at 3 years was 202.5%, and the average soil moisture in natural primary forest was 426.3%. Soil moisture is a critical factor in N_2O production as it affects the availability of O_2 and the activity of soil microorganisms. Higher soil moisture levels can lead to higher N_2O emissions (Ramzan et al., 2020).

N_2O fluxes in the crop fields

Global N_2O emissions from row-crop agriculture are considered to be the greatest contributor to global N_2O flux (Lawrence et al., 2021), with cultivated soils comprising 27% of the total N_2O-N added from all known sources. It might be caused by normal fertilization application only for on-row crops (Shcherbak and Robertson, 2019). Hence, the concentration of N element on-row is typically higher than inter-row crops. Furthermore, fertilization also causes increased production of N_2O. Corollary to this, Winkhart et al. (2022) found that the highest N_2O flux in corn occurred during the early days after planting, resulting from the intensive use of organic manure and N fertilizer by most traditional farmers, which creates an environment that is suitable to the formation of N_2O. Similarly,

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Wu et al. (2022) stated that production increases, either through the process of nitrification or through denitrification, when N fertilizer is applied.

Researchers study showed that total N_2O fluxes during the study period on corn (77-d), peanut (75-d) and cassava (246-d) fields were 2.10 kg N-N_2O ha^{-1}, 0.19 kg N-N_2O ha^{-1} and 0.62 kg N-N_2O ha^{-1} respectively (Table 2). The N_2O flux of corn is higher than peanut and cassava, and this is likely due to the differences in their respective growth and management practices. Corn is a crop that requires a lot of N fertilizer to support its growth and yield. The highest fluxes occurred following basal and top dressing N fertilization in maize regardless of the growing season and forage is previously grown (Grassmann et al., 2020).

Nitrogen fertilizer is a primary source of N_2O emissions from agricultural soils. The higher N_2O flux in corn may be attributed to the higher nitrogen inputs in the form of fertilizer that are typically used to grow this crop. Corn cultivation may be more intensive than peanut and cassava, so corn needs higher N fertilizer inputs than other crops (Deng et al., 2015). In contrast, peanuts and cassava are crops that require relatively less N fertilizer, and therefore may release less N_2O. In the cassava field, the data likewise showed that N_2O flux increased significantly with the application of fertilizer, particularly when followed by rain. Rainwater can contain additional N that can contribute to N_2O production in agricultural sites. Nitrogen deposition from rainwater can increase the availability of N in the soil, which can lead to increased N_2O emissions (Ma et al., 2018).

Researchers study site is located in an area extensively used for agricultural cultivation, which is a tropical region with relatively high rainfall. Areas with high rainfall can cause submergence during intense rainfall, which occurs when the soil's ability to drain water is compromised, often due to factors such as heavy rainfall, poor soil structure, or inadequate drainage (Fukao et al., 2019). Rainfall can increase the water content of the soil, which can affect N_2O production through denitrification processes.

Table 2. Total N_2O fluxes in crop fields on mineral soils

Land use type/Age	Total N-N_2O flux (kg N-N_2O ha^{-1})
Corn (77 days)	2.10
Peanut (75 days)	0.19
Cassava (246 days)	0.62

Groundwater can affect denitrification process, either directly or indirectly by way of: (1) forming a suitable environment for microorganisms to grow and move, (2) restricting the availability of O_2 in the soil micropores, and (3) facilitating the release of C and N substrates through wetting and drying cycles. Yet, soil water limits the presence of O_2 in the soil pores, so the N_2O easily formed in a bit anaerobic condition (Geng et al., 2017). Rainfall caused excessive dampness of the soil, which could bring about denitrification processes, thereby producing N_2O (Geng et al., 2017; Friedl et al., 2020).

N_2O is produced when plant-based N is subjected to the bacterial processes of denitrification and nitrification. Denitrification is the reduction of NO_3^- back into the largely inert N_2 for completing the cycle (Abatenh et al., 2018). The most important factors controlling these processes are N (NH_4^+ and NO_3^-) concentrations in mineral soils, O_2 under partial pressure and, in the case of denitrification, available carbon to fuel the heterotrophic processes (Giles et al., 2012).

In this study, the N_2O fluxes ranged from −0.132 mg N-N_2O m^{-2} d^{-1} in the cassava field to 41.283 mg N-N_2O m^{-2} d^{-1} in the corn field, which received the highest degree of fertilizer application. The N_2O flux from the corn field registered the highest, compared to those coming from the peanut and cassava fields. Generally, the highest N_2O fluxes occurred in the first week after fertilization, and more so when followed by rain. The mean peak N_2O flux in the corn field was 23.499 mg N-N_2O m^{-2} d^{-1} at the beginning of planting, while in the peanut and cassava fields, the corresponding values were 0.550 mg N-N_2O m^{-2} d^{-1} and 1.278 mg N-N_2O m^{-2} d^{-1} respectively. The summary data on N_2O fluxes and environmental variables are shown in Figure 4, 5 and 6. N_2O flux on-row in the corn field was higher than in the inter-row, especially at the beginning of planting. In comparison, the N_2O flux in the cassava field did not show any significant difference between on-row and inter-row.

Comparison of mineral and peatland N_2O fluxes in the peatland fields

The N_2O flux values presented in the Table 3 suggest that there are significant differences in N_2O emissions among different land use types and ages. In mineral soils, corn has the highest N_2O flux at 9.95 kg N-N_2O ha^{-1} y^{-1}. In peatland soils, *A. crassicarpa* (1 year) has the highest N_2O flux at 13.85 kg N-N_2O ha^{-1} y^{-1}. The application of chemical fertilizer is the prevailing farm practice in cropland in the mineral soil around 5 ton ha^{-1} of manure is applied on cassava fields and 500 kg ha^{-1} of phonska is applied on peanut fields. The fertilizer dose of corn fields is 373 kg ha^{-1} of urea, 92 kg ha^{-1} of SP36, and 186 kg ha^{-1} of phonska. This is because of fertilizer that makes N_2O flux on corn fields the highest than others.

Based on the N_2O flux values presented in the Table 3 and the fertilizer doses provided, the amount of N lost from the fertilizer in the form of N_2O can be calculated for each crop. For corn, with an N_2O flux of 9.95 kg N-N_2O ha^{-1} y^{-1} and a fertilizer dose of 373 kg ha^{-1} of urea, 92 kg ha^{-1} of SP36, and 186 kg ha^{-1} of phonska, the amount of N lost as N_2O is estimated to be 1.89 kg N ha^{-1} y^{-1}. For peanut, with an N_2O flux of 0.90 kg N-N_2O ha^{-1} y^{-1} and a fertilizer dose of 500 kg ha^{-1} of phonska, the amount of N lost as N_2O is estimated to be 0.07 kg N ha^{-1} y^{-1}. Lastly, for cassava, with an N_2O flux of 0.92 kg N-N_2O ha^{-1} y^{-1} and a fertilizer dose of 5 tons ha^{-1} of manure (assuming 0.5% N content), the amount of N lost as N_2O is estimated to be 0.00023 kg N ha^{-1} y^{-1}. A study in Chile by Salazar et al. (2021) found that the N fertilizer efficiency (NFE) in maize was 45.5% in the maize-fallow rotation and 41.7% in the maize-cover crop rotation. The study also found that the NO_3^- leaching losses were 5.4 and 4.5 kg N ha^{-1} in the maize-fallow and maize-cover crop rotations, respectively. Bijay-Singh and Craswell (2021) found that only a portion of the fertilizer N is directly lost from the cropping system via leaching and/or in gaseous forms (N_2O and NH_3).

The P addition has stimulated the activities of nitrifying or denitrifying bacteria due to the relief

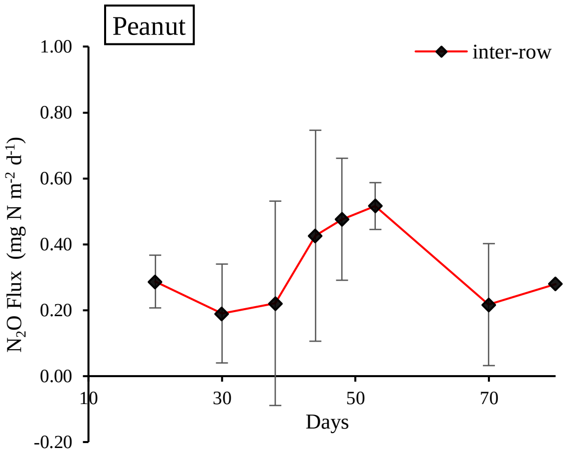

Figure 4. N_2O flux from peanut field

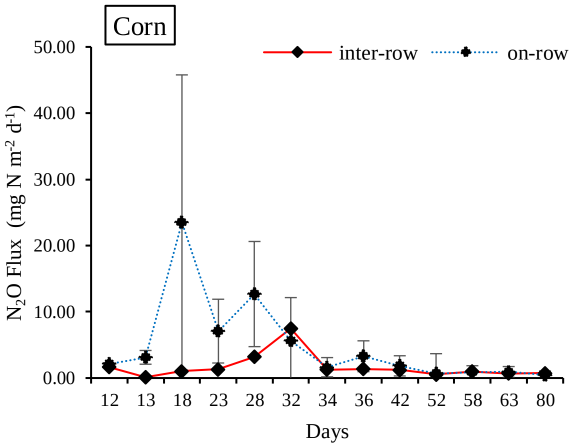

Figure 5. N_2O flux from corn field

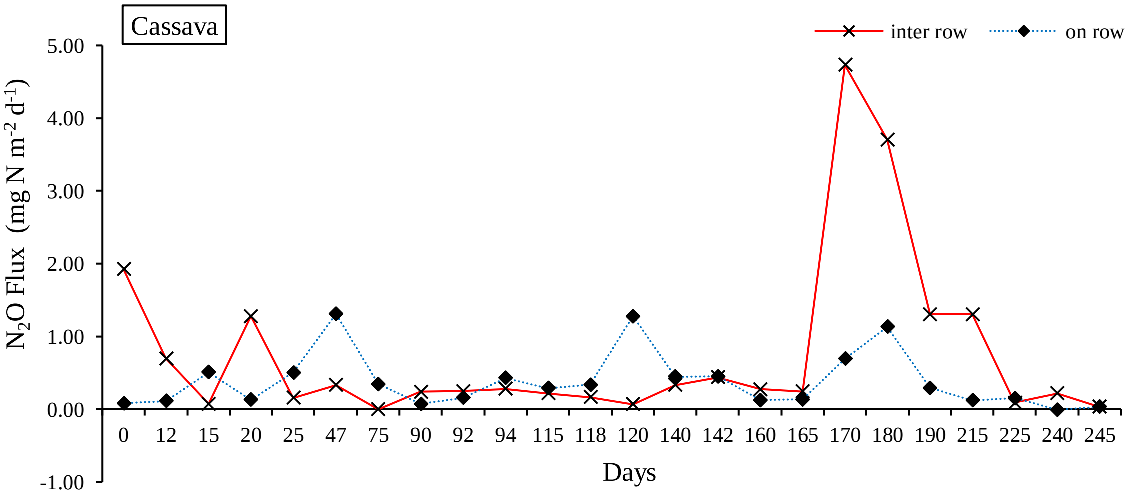

Figure 6. N_2O flux from cassava field

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from their P shortage. Phospat addition may lead to increases in nitrification or denitrification activity, which results in higher N_2O and NO emissions (Mori et al., 2010). The addition of fertilizer P significantly increases soil N_2O emissions. Increased soil moisture and the application of N fertilizer also increase N_2O emissions. Combined applications of fertilizers P and N indicate higher N_2O emissions compared to their applications on a single basis (Sarkar et al., 2017). This is attributed to the alteration of soil properties and microbial activity, leading to increased rates of nitrification and denitrification. The presence of both P and N fertilizers can enhance N availability and microbial activity, creating favorable conditions for N_2O production (Zhou et al., 2020). Additionally, the interaction between P and N fertilizers can disrupt the N cycle and reduce N uptake by plants, resulting in more N available for N_2O emissions (Grohskopf et al., 2019). By significant addition of N, it will directly increase N substrates to nitrification and denitrification process and it would probably be rising N_2O (F. Wang et al., 2014). This also happens when adding P fertilizer on soil. Increasing soil available P after P fertilizer application significantly will increase soil microbial biomass carbon.

In the corn field, N_2O flux occurred within around three weeks of fertilizer application, suggesting increased N availability. Furthermore, peak N_2O emissions occurred within heavy daily rainfall events ±2400 mm. Soil aeration following saturation is important for the diffusion and release of GHGs. Continuous saturation leads to strong anaerobic conditions in the soil, which can lead to the full reduction of NO_3^- to N_2 (Crézé and Madramootoo, 2019). Likewise, in the *Acacia* plantation, N addition significantly increased the rates of nitrification (Mori et al., 2017).

The N_2O flux values for *A. crassicarpa* plantations decrease as the plantation ages. This could be due to the establishment of a stable soil microbial community, which can reduce N_2O emissions. Additionally, the reduction in fertilizer use as the plantation ages can also contribute to the decrease in N_2O emissions. Research results from Ishizuka et al. (2021) also show that N_2O emissions within 1 year of *Acacia* plantation can potentially emit large amounts of N_2O emissions. However, the large amount of N_2O emission decreases rapidly and reaches the same level of equilibrium as the flux observed at the age of 3 years of *Acacia* plantation. The fertilizer addition significantly increased N_2O emission *Acacia* plantation in the first year. However, in the third year, soil N_2O emissions significantly decreased (Zhang et al., 2014). The difference in N_2O flux between that from the *A. crassicarpa* 3 years and that from a similar plantation but with no fine root and litter (-R-L) reflects differences in rate of the respiration and root exudation (Sumawinata et al., 2014).

The values for natural primary forests also show variation, with slightly lower N_2O flux values for the “natural primary forest- R-L” category. This could be due to differences in vegetation cover and soil moisture content in the different areas. Moreover, in tropical regions, plants and microbes compete fiercely for resources. As a result of this competition, plants tend to absorb more nutrients while losing less nitrogen gas, but the extent of their absorption depends heavily on their density. In a particular, the higher root density significantly increases the competition for nitrogen uptake through roots. It can be inferred that biotic factors play a vital role in this competition, and the formation of mycorrhiza and root density is critical in shifting

Table 3. Total N_2O fluxes in agricultural land on peatland soils

Land use type/Age	Total N_2O flux (kg N-N_2O ha^{-1} y^{-1})
Mineral soils:	
Corn (77 days)	9.95
Peanut (75 days)	0.90
Cassava (246 days)	0.92
Peatland soils:	
A. crassicarpa (1 year)	13.85
A. crassicarpa (3 years)	6.65
A. crassicarpa (3 years-R-L)	2.87
Natural primary forest	5.66
Natural primary forest-R-L	4.31

Note: -R-L = without fine root and litter

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the acquisition of nitrogen to the roots (Netherway et al., 2021).

In a natural primary forest, the nutrient cycling process is often controlled by a complex network of interactions between plants, microbes, and animals, which can help to reduce nitrogen losses and maintain a relatively stable nitrogen balance. Additionally, natural forests usually have a lower soil disturbance compared to agricultural or plantation areas, which can limit the exposure of soil to air and reduce the conditions for N_2O production. Furthermore, the presence of fine roots and litter can contribute to N_2O emissions. Because it contains large amounts of carbon and other nutrients that can support the growth of microorganisms and promote the conversion of N_2O to harmless gases like N_2 or NO. Microorganisms obtain N from root and soil residues. The soil continuously received root exudates from dead fine roots. Therefore, the natural primary forest without fine roots and litter may lead to a slight increase in N_2O emissions (Kim et al., 2022).

Overall, the results highlight the importance of considering land use type and age when assessing N_2O emissions. Management practices such as fertilizer use, soil disturbance, and vegetation cover can all have significant impacts on N_2O emissions (Roy et al., 2014; Krauss et al., 2017; Menegat et al., 2022). The management practices in the agricultural field are crucial in impacting N_2O emissions since it dictates the quantity of soil N input, which can alter the soil environment and microbial conditions. X. Wang et al. (2021) stated that management variables comprise the quantity and sort of fertilizer applied, the types of crops grown, and the tilling procedures used, which can also impact the amount of crop residue left on the soil surface. This section is crucial that the effects of specific agricultural management practices can affect N_2O emissions.

The impact of N fertilizer on N_2O flux emissions in agricultural land

In agricultural land, increases in N_2O emissions typically follow N fertilization but only for a short time. After this time, the emission rates are reduced, fluctuating around a low baseline level which is independent of the amount of fertilizer applied (Ruiz et al., 2021). Mineral N applications, along with organic matter amendments, generally increase total denitrification and N_2O production. N_2O emissions from the soil can vary by order of magnitude in a location, both spatially and temporally. N_2O emissions are predicted not only from fertilization but also from biological/bacterial activity, which plays an important role in N_2O production (Harris et al., 2022). The results of this study suggest that as farmers apply excessive N-fertilizer, the formation of N_2O is thus increased. Beside the observable high levels of NH_4^+ and NO_3^-, the excess N concentration in the corn field can also be seen from the visible presence of succulent plant stems in the study area.

Nevertheless, emission peaks did not exclusively occur immediately after fertilizer application. Likewise, some studies have shown that N_2O emission from agricultural soil is significantly increased by the application of synthetic N fertilizers (Linn and Doran, 1984; Bronson et al., 2021). Moreover, Hassan et al. (2022) highlighted that the potential for N_2O emissions from agricultural soils may be lowered by changes in fertility and irrigation management. Fertilization and drainage can be coordinated so that drainage does not occur soon after fertilization and so that drainage does not greatly increase N_2O emissions during the growing season.

The increasing levels of atmospheric N_2O are of particular concern due to its considerably higher GWP relative to CO_2. For example, over a 20-yr period, 1 kg of N_2O will have 275 times the influence on global warming as 1 kg of CO_2 (Solecki et al., 2022). Aside from emitting N_2O, the impacts of excessive fertilizer application can also damage plants, and would deserve the farmers, ultimately. NO_3^- leaching is also important from a water-quality perspective because it contributes to aquatic eutrophication and can pose a health risk to humans.

Nitrogen cycling reactions can affect volatilization by influencing the amount of NH_3 available to volatilize. The process of volatilization of NH_3 occurs not only in lowland rice but also in other crops. A study by Santos et al. (2020) found that NH_3 loss differed among N sources in corn, suggesting that NH_3 volatilization may occur in corn fields. Janke et al. (2022) pointed out that volatilization losses from urea can be reduced by in-soil banding or by incorporation of the fertilizer immediately after application. However, under a reduced tillage system, banding or incorporation leads to undesirable soil disturbance. At any rate, land management practices or systems that reduce GHG emissions would aid in slowing climate change. Guenet et al. (2021) stated that impacts

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on farmers and land managers give part of which contributes to indirect N_2O emissions, through excess N, changes in loss NO_3^- leaching and N_2O emissions that must be considered.

CONCLUSIONS

This review examines the significant contributions of different sectors to N_2O emissions in Indonesia and emphasizes the dominant role of agriculture as the primary source. Several factors affecting on N_2O both on mineral and peat soil are soil properties (soil temperature, moisture), soil input such as organic matter application and N fertilizing, and agriculture practice management such as soil tillage system. Nitrogen fertilizing takes a significant effect on N_2O emission. Sustainable agricultural practices, including precise N fertilizer management and minimizing soil disturbance, are crucial for reducing N_2O emissions from agricultural activities. Additionally, addressing N_2O emissions in Indonesia requires a comprehensive approach that encompasses clean energy transitions, land use policies, and improved waste management. The findings of this review provide valuable insights for policymakers, researchers, and practitioners, offering a foundation for developing effective strategies to mitigate N_2O emissions in Indonesia and similar tropical farming systems. By implementing these strategies, Indonesia can make significant progress in reducing its overall N_2O emissions and contribute to global efforts in combating climate change.

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