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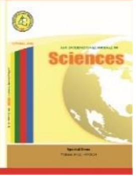

THE IMPACT OF ORGANIC FERTILIZERS ON NITROUS OXIDE EMISSIONS AND CLIMATE CHANGE: A REVIEW AND RECOMMENDATIONS

Huynh Thi Thanh Truc[1], Trinh Thi Hong[1], Nguyen Hong Van[1]
[1]*An Giang University, VNU-HCM*

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ABSTRACT

Organic fertilizers have a significant impact on climate change by influencing greenhouse gas emissions from agricultural systems. Current studies indicate that organic fertilizers, including compost, livestock manure, and biofertilizers, have the potential to reduce nitrous oxide emissions compared to chemical fertilizers. This paper aims to provide a comprehensive overview of the impact of organic fertilizers on nitrous oxide emissions and offers recommendations for effective practices. We analyze studies on the combination of organic fertilizers with irrigation practices to mitigate nitrous oxide emissions in semi-arid climates, focusing on factors such as fertilizer type, soil temperature and moisture, and irrigation methods during cultivation. The paper also examines the effects of organic fertilizers on soil properties, such as soil structure and water retention capacity. Through this review, we highlight both the benefits and limitations of organic fertilizers and propose strategies to optimize their use in reducing greenhouse gas emissions and addressing climate change.

1. INTRODUCTION

Fertilizer application is essential for ensuring crop yield and soil quality. However, the increasing use of fertilizers, particularly nitrogen-based ones, driven by population growth and food demand, has led to increased N_2O emissions from agricultural soils, contributing to global climate change.

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential 298 times greater than carbon dioxide (CO_2) over a 100-year period, accounting for 6% of global radiative forcing (WMO, 2023). Since the pre-industrial era, N_2O concentrations have increased by 124%, with anthropogenic emissions mainly coming from nitrogen addition to croplands, which has risen by 30% over the past four decades to 7.3 teragrams per year. Strategies to mitigate greenhouse gas emissions include efficient irrigation techniques and fertilization practices, which help optimize crop growth and reduce N_2O emissions.

N_2O is produced primarily through nitrification and denitrification, which depend on the nitrogen content in the soil (Akiyama et al., 2000). Nitrogen fertilization affects NH_4^+ and NO_3^- availability: higher NH_4^+ levels promote nitrification, leading to reduced N_2O emissions (Liu et al., 2005), while higher NO_3^- levels lead to increased emissions (Carmo et al., 2005). In contrast, increased nitrogen application results in higher plant biomass, leaving more crop residues in the soil, which can increase long-term N_2O emissions (Hellebrand et al., 2008). Fertilizer type also plays a role; ammonium-based fertilizers emit N_2O more slowly compared to nitrate-based ones.

Chemical nitrogen fertilizers are major contributors to GHG emissions from agricultural soils. Studies show that organic fertilizers can reduce N_2O emissions compared to inorganic fertilizers or unfertilized soils. The effect of organic fertilizers on N_2O emissions depends on factors such as the C ratio, source (plant or animal), and soil conditions like texture, moisture, and temperature. Long-term organic fertilization results in carbon accumulation, stabilizing nitrogen and increasing denitrifying microorganisms, thus reducing N_2O emissions. For example, replacing chemical fertilizers with organic ones reduced N_2O emissions by 70% in a double-cropping rice system and reduced emissions in oil crops (Nyamadzawo et al., 2014).

However, other studies suggest that organic fertilization can increase N_2O emissions by increasing soil organic matter and promoting denitrification (Zhang et al., 2018). Animal manure, for instance, was found to increase N_2O emissions by 17.7% (Shakoor et al., 2021). The combination of organic and inorganic fertilizers has also been found to result in higher N_2O emissions than either used alone (Lazcano et al., 2016; Bouwman et al., 2002).

The question remains whether replacing chemical nitrogen fertilizers with organic alternatives is an effective strategy for reducing N_2O emissions and how best to use organic fertilizers to optimize crop production while mitigating climate impact. This study aims to quantify factors influencing N_2O emissions, examine the effects of organic fertilizers on emissions, soil properties, and nitrogen cycle-related microorganisms, and determine optimal organic fertilizer practices for sustainable agricultural use.

2. METHODOLOGY

The research methodology of this review involves a meta-analysis of published studies examining the impact of replacing chemical fertilizers with organic fertilizers on N2O emissions. The authors gathered studies from reputable scientific sources, focusing on semi-arid and other global regions. The selected studies were evaluated based on data quality, research methods, and the influence of relevant variables. A systematic review approach ensured an objective synthesis, enabling comparison across different geographical and climatic conditions. Both quantitative and qualitative analyses were conducted to identify general trends and factors affecting N2O emissions when using organic fertilizers.

Denitrification is the process of converting NO_3^- to N_2, mediated by heterotrophic denitrifying bacteria and fungi, which are key microbial processes in the soil nitrogen cycle. This process can be complete, producing N_2, or incomplete, resulting in the formation of NO and N_2O. Denitrification is promoted by high NO_3^- concentrations, high availability of labile carbon, and low oxygen conditions. Enhanced denitrification leads to increased N_2O production. The reduction of N_2O to N_2 is easily affected by the presence of O_2, and the nosZ enzyme responsible for this reaction is inhibited in low pH soils (Hu, Chen, & He, 2015). Therefore, agricultural practices that create anaerobic conditions and increase soil pH can help mitigate N_2O emissions.

Although denitrification accounts for the majority of N_2O produced in soils, nitrification can also produce N_2O under limited oxygen conditions. Bremner presented findings from multiple studies indicating that nitrifying microorganisms can significantly contribute to N_2O emissions from soils. According to Bremner, N_2O production from nitrification increases with higher soil pH and organic matter content, as well as increased soil moisture (from air-dried to field capacity) and soil temperature (5–40°C), through the addition of nitrifiable nitrogen, animal manure, and plant residues (Bremner, 1997). N_2O production from nitrification can be reduced by using nitrification inhibitors.

Under anaerobic conditions, the concentration of NO_2^-, a toxic compound, increases in the soil (Khalil et al., 2004), and it can be utilized by nitrifying microorganisms to produce N_2O and NO during nitrification (Snyder et al., 2009). Both nitrification and denitrification produce N_2O as a byproduct or intermediate, and these processes can occur simultaneously in soils. However, nitrification is an aerobic process requiring oxygen, while denitrification is an anaerobic process inhibited by high oxygen levels. In soil, oxygen levels are largely controlled by soil moisture: higher soil moisture leads to lower oxygen availability, and vice versa. Oxygen levels are also influenced by microbial respiration; during periods of high microbial activity, soil oxygen is consumed, leading to increased N_2O production from nitrification. Denitrifiers also consume N_2O when soil moisture is very high. Therefore, soil moisture plays a significant role in determining which process occurs and the final amount of N_2O emitted from soil. Soil bulk density, texture, and structure strongly influence soil moisture, oxygen concentration, and gas exchange, thereby affecting microbial N_2O production or consumption. Other environmental factors, such as pH, temperature, substrate availability (NH_4^+, NO_3^-, and soil carbon), crop rotation, tillage, fertilizer source and rate, and timing of nitrogen application also govern the microbial production and consumption of N_2O (Liu et al., 2006).

Thus, much of the difficulty in predicting, measuring, and managing N_2O emissions lies in understanding the interactions among these factors.

3. RESEARCH CONTENT

3.1 The N cycle and N_2O production in soil

N_2O is primarily produced through two pathways: nitrification and denitrification.

Nitrification is the oxidation process of NH_4^+ to NO_3^- (Figure 1), carried out by two distinct groups of autotrophic bacteria: ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB). In addition, ammonia-oxidizing archaea (AOA) have also been identified as participants in the nitrification process. AOB are sensitive to low pH and are more prevalent in soils treated with inorganic fertilizers, whereas AOA dominate in acidic soils and thrive when NH_4^+ is present through the decomposition of organic nitrogen sources.

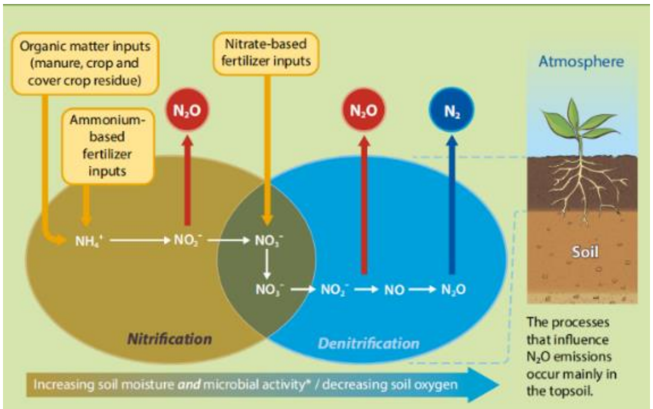

Figure 1. Processes of N_2O emissions occurring in soil (Lazcano et al., 2021)

Denitrification is the process of converting NO_3^- to N_2, mediated by heterotrophic denitrifying bacteria and fungi, which are the main microbial processes involved in the soil nitrogen cycle. This process can be complete, producing N_2, or incomplete, resulting in the formation of NO and N_2O. Denitrification is promoted by high NO_3^- concentrations, high availability of labile carbon, and low oxygen conditions. When denitrification is enhanced, it leads to increased N_2O production. The reduction of N_2O to N_2 is easily affected by exposure to O_2, and the nosZ enzyme responsible for this reaction is inhibited in low pH soils (Hu et al., 2015). Therefore, agricultural practices that create anaerobic conditions and increase soil pH help mitigate N_2O emissions.

Although denitrification accounts for the majority of N_2O produced in soils, nitrification can also produce N_2O under limited oxygen conditions. Bremner (1997) presented results from several studies indicating that nitrifying microorganisms can significantly contribute to N_2O emissions from soils. According to this author, N_2O production from nitrification increases with higher soil pH and organic matter content, as well as increased soil moisture (ranging from air-dry to field capacity) and soil temperature (5–40°C), through the addition of nitrifiable nitrogen, animal manure, and plant residues. N_2O produced by nitrification can be reduced by using nitrification inhibitors.

3.2 Factors affecting N_2O emissions

Microbial communities involved in nitrification and denitrification, which lead to N_2O emissions, are influenced by various environmental conditions. These conditions directly impact the activity of specific microorganisms, resulting in immediate changes in nitrification and denitrification rates, as well as the N_2/N_2O ratio.

3.2.1 Environmental factors: Microbial communities

Nitrification is performed by autotrophic bacteria in two stages: NH_4^+ is first oxidized to NO_2^- by Nitrosomonas, Nitrosococcus, and Nitrosospira, and then NO_2^- is further oxidized to NO_3^- by Nitrobacter, Nitrosospira, and Nitrococcus (Moreira & Siqueira, 2006). During this process, the NO_2^- concentration initially increases and then decreases as NO_3^- is formed, with negligible N_2O production (Bremner, 1997).

Denitrification is performed by microorganisms that use different energy sources, such as light, inorganic nitrogen, or organic carbon. Common soil denitrifiers are organotrophs, especially

Pseudomonas species, due to their flexibility and competitive advantage in utilizing carbon substrates. Other denitrifiers include Alcaligenes, closely related to Pseudomonas (Abdalla, Smith, & Williams, 2011).

Soil microorganisms also influence N_2O emissions by affecting the N_2/N_2O ratio during denitrification. Pseudomonas denitrificans G1 was found to effectively remove NO_3^- and NO_2^- under anaerobic conditions, with efficient denitrification resulting in N_2 as the final product (Chen et al., 2018). Environmental factors, such as the C/N ratio, dissolved oxygen, salinity, and pH, also affect soil bacteria activity and distribution (Cameron et al., 2013).

3.2.2 Available carbon in soil

The capacity for nitrification and denitrification in soils increases with rising soil organic carbon (SOC) levels, especially the water-soluble fraction, as it provides an easily available source for bacteria, enhancing microbial activity and creating anaerobic conditions needed for denitrification. Chen et al. found that N_2O emissions accounted for 35% and 50% of total nitrogen emissions at SOC levels of 28 mg kg^{-1} and 300 mg kg^{-1}, respectively, in a rice field in southern China (Chen et al., 2014).

The availability of organic carbon determines whether denitrifying bacteria produce primarily N_2 or N_2O. Weier et al. observed that higher glucose-C levels led to a higher N_2/N_2O ratio in soils, indicating enhanced N_2O consumption (Weier et al., 1993). Biochar, a carbon-rich material, also affects N_2O emissions by altering the soil C/N ratio. Feng et al. found that N_2O emissions decreased with increased biochar application in maize fields, with cumulative emissions decreasing significantly as biochar rates increased (Feng et al., 2017).

3.2.3 C/N Ratio

Nitrogen transformation in soil involves assimilation, where microorganisms uptake nitrogen and convert it into organic nitrogen, and mineralization, where organic nitrogen is converted into NH_3. The balance between these processes depends on the soil C/N ratio (Baggs et al., 2000). A high C/N ratio from straw on the soil surface promotes nitrogen assimilation, reducing denitrification and N_2O emissions, while low or absent straw can increase nitrogen availability for nitrification and denitrification, potentially raising N_2O emissions.

3.2.4 Soil temperature and moisture

Soil temperature and moisture significantly influence nitrification and denitrification processes, affecting microbial activity and N_2O production. Nitrogen transformation rates increase with rising temperatures, and N_2O emissions rise exponentially between 0–50°C (Akiyama et al., 2000; Liu et al., 2011), leading to a close relationship between seasonal N_2O fluxes and temperature variations (Wolf & Brumme, 2002). Increased soil temperatures also stimulate microbial respiration, enhancing anaerobic microsites suitable for denitrification. N_2O emissions generally increase after nitrogen fertilization, particularly under wet conditions, with peak emissions observed following rainfall or during periods of high soil temperatures (Perdomo et al., 2009; Schwenke et al., 2016).

High soil moisture typically leads to increased N_2O emissions due to enhanced nitrification and denitrification (Davidson & Swank, 1986). However, very high moisture levels can inhibit microbial activity, reducing N_2O production, while alternating wet and dry conditions can lead to increased emissions (Brentrup et al., 2000). Studies show that replacing chemical fertilizers with organic fertilizers reduces N_2O emissions when annual rainfall ranges from 400–800 mm or exceeds 800 mm (He et al., 2023).

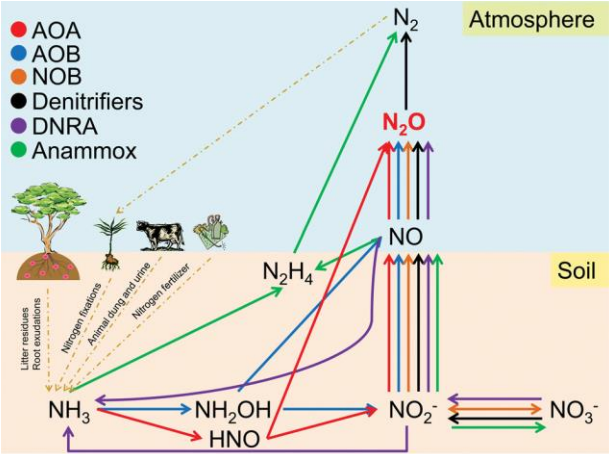

Figure 2. Simplified schematic of major microbial pathways in N_2O production and nitrogen cycling in soil ecosystems (Hu, Chen, & He, 2015). AOA (Archaea oxidizing ammonia), AOB (Bacteria oxidizing ammonia), NOB (Bacteria oxidizing nitrite).

3.2.5 Soil pH

Soil pH is a critical factor influencing N_2O emissions because the enzyme responsible for reducing nitrous oxide is inhibited at low pH and in the presence of O_2. Generally, if denitrification is the primary source of N_2O, higher pH values tend to reduce N_2O emissions, whereas if nitrification is the main process producing N_2O, an increase in soil pH stimulates N_2O production. Clough et al. studied the impact of pH on N_2O emissions from silt loam soil by applying lime to raise soil pH. They found that autotrophic nitrification was limited at soil pH < 4.5 (Clough et al., 2003). Liming acidic soils can promote nitrification while simultaneously reducing denitrification rates as soil pH decreases. Soil pH determines whether NO_2^- and NO_3^- are chemically reduced to N_2O or to N_2. Under acidic conditions, N_2O is emitted by denitrifying bacteria, such as *Pseudomonas* (Stein et al., 2003). Therefore, the N_2O/N_2 ratio is higher in acidic soils (pH < 6.0), while N_2O and N_2 emissions are nearly equal at pH 6.0 (Rochester et al., 2003). At pH < 6.0, N_2O is the only denitrification product, but at higher pH values, N_2 becomes the main product of denitrification (Šimek et al., 2002).

3.2.6 Soil Texture

Water-Filled Pore Space (WFPS) is crucial for assessing soil wetness and its impact on N_2O emissions. High WFPS levels (>60%) displace available oxygen in soil pores, creating anaerobic conditions that favor N_2O production through denitrification. Bateman and Baggs found that in fertilized silt loam soil, 70% WFPS led to denitrification as the sole source of N_2O, while nitrification was predominant at 35%–60% WFPS (Bateman & Baggs, 2005). Similarly, Ruser et al. reported increased N_2O emissions from denitrification when WFPS exceeded 60–70%, and a higher N_2/N_2O ratio at moisture above 90% due to N_2O reduction under anaerobic conditions (Ruser et al., 2006). These findings emphasize the strong correlation between WFPS, microbial activity, and N_2O emissions (Davidson & Swank, 1986).

Soil texture also plays a significant role in N_2O emissions. Fine-textured soils, such as clay, retain more water, promoting anaerobic conditions and higher N_2O emissions compared to sandy soils (Brentrup et al., 2000). Tan et al. found that N_2O emissions after rainfall were four times higher in clay loam soils than in sandy loam soils (Tan et al., 2009). The denitrification rate also tends to decrease faster in finer soils as WFPS declines (Weier et al., 1993; Parton et al., 1996). Additionally, soil texture affects N_2O emissions by influencing soil organic carbon (SOC) content and microbial community structure (Xu et al., 2013).

3.3 Agricultural management factors

3.3.1 Tillage and crop residue management

Tillage practices affect soil structure, aeration, microbial activity, residue decomposition, nitrogen mineralization, and soil temperature and moisture. The presence or absence of tillage, as well as the timing of tillage, can impact N_2O emissions.

A study in a maize-wheat rotation field in Brazil showed that N_2O emissions were 107% higher when nitrogen was applied to no-till soil compared to tilled soil (Grave et al., 2018). In a subtropical Oxisol in Brazil, post-harvest N_2O emissions were three times higher in no-till areas compared to tilled areas (Escobar et al., 2010). This can be attributed to the higher denitrifier population in no-till soil, while N fertilizer is rapidly taken up by weeds due to the absence of tillage. In arid climates such as California, transitioning from conventional tillage to reduced or no-tillage during the first ten years led to increased N_2O emissions, but emissions later decreased with continued no-till practices (Van et al., 2013).

Higher soil moisture due to crop residues in no-till soils (Baggs et al., 2006) can increase microbial activity near the soil surface. The combination of maize and wheat straw significantly raised soil temperature due to their heat-retaining properties, which may have stimulated the enzymatic activity of nitrifying and denitrifying bacteria, enhancing microbial N_2O production. In tilled soils, this mechanism is minimized due to the aeration of the upper soil layer, increasing O_2 levels and consequently reducing N_2O emissions. Choudhary assessed the long-term effects of continuous tillage on N_2O emissions from maize fields in New Zealand. Average annual N_2O emissions from 34-year and 17-year-old fields were 2.37 and 3.42 kg N_2O ha^{-1}, respectively (Choudhary et al., 2001). In the 34-year fields, intensive and continuous tillage led to low surface residue, reduced water-holding capacity, and depleted C and N content, which may have limited denitrification.

3.3.2 Irrigation

Irrigation involves both high-water-use systems (such as rainfall, furrow irrigation, flooding, sprinkler, and micro-sprinkler irrigation) and low-water-use systems (such as surface and subsurface drip irrigation). Studies have shown that N_2O emissions from almond trees are significantly reduced with micro-sprinkler irrigation compared to drip irrigation (Alsian et al., 2013). A study on tomato cultivation found significant reductions in N_2O emissions with drip irrigation compared to furrow irrigation due to improved water and fertilizer use efficiency via fertigation (Kennedy, Suddick, & Six, 2013). Another study in vegetable soils in China showed that N_2O emissions were reduced by 16.4% and 60.9% with mulched micro-irrigation and filtered drip irrigation, respectively, compared to furrow irrigation (Ye et al., 2019).

Irrigation affects denitrification by altering soil moisture and temperature. An increase in WFPS leads to lower oxygen concentrations, creating anaerobic conditions that promote denitrification. Enhanced soil microbial activity can also lead to decreased soil oxygen levels (Trost et al., 2013). Proper irrigation techniques allow precise application of nitrogen and water according to crop requirements, thus reducing N_2O emissions.

3.3.3 Fertilization

The impact of fertilizers on N_2O emissions depends on the type of fertilizer, timing of application, and the amount applied. Nitrogen fertilizers include synthetic fertilizers (e.g., urea, ammonium nitrate, ammonium sulfate, and NPK fertilizers), organic fertilizers (e.g., compost, municipal solid waste compost, manure, and crop residues), and livestock or poultry waste. The type of fertilizer affects N_2O emissions. Fertilizer application adds nitrogen to the soil, contributing to increased N_2O emissions (Cole et al., 1997). Generally, ammonium-based fertilizers result in slower N_2O emissions compared to nitrate-based fertilizers. Studies have shown that nitrate fertilizers produce more N_2O compared to amide (urea) or ammonium fertilizers, with ammonium nitrate causing stronger and quicker emissions than urea (Zanatta et al., 2010).

The timing of fertilization influences nitrogen use efficiency and crop yield. Schwenke reported that applying urea late at flowering reduced N_2O emissions by 67%–81% compared to applying urea at seeding. However, late application tended to result in lower nitrogen uptake, grain yield, and protein content due to dry soil conditions mid-season (Schwenke et al., 2019). Split nitrogen application (33% at seeding; 67% at flowering) reduced N_2O emissions by 59% compared to urea applied at seeding, while maintaining nitrogen uptake, grain yield, and protein content. Applying mineral or organic fertilizers before or during seeding can increase N_2O emissions due to the high amount of nitrogen in the soil during the early growth stages when plants cannot fully assimilate it, and also because rainfall can increase soil moisture, enhancing N_2O emissions.

Fertilizer placement depth also affects N_2O emissions. Applying nitrogen at depths greater than 5 cm can reduce emissions, especially in humid climates (Van et al., 2013). Emissions are lower when nitrogen is deposited at a depth of 10 cm compared to surface or 5 cm depth applications. Applying fertilizer at 10 cm depth increases N_2O residence time in the soil and enhances the likelihood of N_2 reduction (Chapuis et al., 2007).

3.4 Organic fertilizer sources and n₂o emissions

The use of organic fertilizers is an important practice to nourish and improve soil fertility. There is substantial scientific evidence supporting the role of organic matter in enhancing soil quality and mitigating climate change compared to inorganic fertilizers. As a result, there has been an increase in the use of fertilizers derived from organic waste in recent years (Lupton et al., 2017). Organic fertilizers include manure, compost, and other natural soil amendments.

Organic fertilizers are primarily derived from livestock and poultry manure, which has become a major source of organic emissions in most countries. Animal manure provides nutrients for plants, such as organic and inorganic nitrogen. However, the type and amount of nitrogen in animal manure vary greatly. Manure is a heterogeneous material composed of a mixture of feces and urine, leading to different proportions of NH_4^+, NO_3^-, urea, and organic nitrogen from undigested proteins, amino acids, and nucleic acids. The ratio of inorganic to organic nitrogen depends on the type of animal, diet, nitrogen excretion rate, bedding materials, and manure processing methods (Oenema et al., 2005). Total nitrogen content in poultry manure is generally higher than in cattle or dairy manure or pig manure (Whalen et al., 2019), and liquid manure contains lower organic nitrogen and higher NH_4^+ content than solid manure. Even within the same animal type, bedding materials and manure processing, treatment, and storage significantly affect the total nitrogen content and its forms. Manures treated aerobically through composting or vermicomposting contain relatively lower organic nitrogen and higher NO_3^- compared to untreated raw manure.

Although organic waste has nutritional value, poor use and management of organic fertilizers can lead to reduced nitrogen use efficiency and increased N_2O emissions. In India, it is estimated that 15,309 Gg CO_2-Ceq per year is emitted directly as N_2O from livestock manure, accounting for approximately 20% of the country's annual N_2O emissions. In the United States, livestock manure produces 6,837 Gg CO_2-Ceq as N_2O annually, representing 2.2% of the total national emissions (Thangarajan et al., 2013). However, emission factors can vary significantly depending on the physicochemical characteristics of organic fertilizers and environmental conditions (Prentice et al., 2008).

3.5 Impact of raw organic fertilizers on n₂o emissions

3.5.1 Impact of Raw Manure

Raw materials such as animal manure provide significant amounts of NH_4^+, which directly affects microbial denitrification. NH_4^+ is gradually released through the transformation of organic nitrogen in manure after application (Ouyang et al., 2019). Ammonia-oxidizing microorganisms are particularly sensitive to the availability of NH_4^+. Therefore, manure often increases the abundance and activity of ammonia oxidizers, leading to accelerated nitrification (Chu et al., 2007). The functional gene responsible for ammonia oxidation, the first step of nitrification, is *amoA*. Higher nitrification rates result in increased availability of NH_2OH, NO, and NO_3^- (substrates for N_2O production).

Animal manure contains varying amounts of carbon, with labile carbon often comprising 35% of the total carbon in manure (Miller et al., 2009). While stable carbon can reduce N_2O emissions by promoting nitrogen immobilization, relatively labile carbon sources like cellulose stimulate N_2O release by promoting denitrification (Wei et al., 2020). Labile carbon in animal manure has also been observed to promote the reduction of N_2O to N_2 by increasing the abundance of nosZ-carrying bacteria. The reduction of N_2O to N_2 is directly influenced by soil pH, as *nosZ* is inhibited in acidic soil conditions. Long-term use of inorganic fertilizers can lead to soil acidification and increased N_2O emissions. Conversely, long-term use of organic fertilizers, such as manure, can mitigate acidification and reduce N_2O emissions (Wang et al., 2019).

Liquid manure contains lower levels of organic nitrogen and higher proportions of NH_4^+ compared to solid manure. Liquid manure, with higher moisture content, often creates anaerobic conditions more quickly, triggering N_2O emissions (Lazcano et al., 2016).

3.5.2 Impact of treated manure on N₂O emissions

Treated manure, such as compost or vermicompost, affects N_2O emissions differently compared to raw manure due to changes in its physicochemical properties. Composting involves rapid microbial decomposition of organic waste under aerobic conditions, making the final product more stable with lower labile carbon and nitrogen, a higher NO_3^-/NH_4^+ ratio, and a lower C/N ratio (Gómez-Brandón et al., 2008; Ye et al., 2020). These changes alter the soil microbial community, often causing a short-term increase in nitrifying and denitrifying bacteria (Braker et al., 2011). However, applying composted pig manure to clay loam soil resulted in similar N_2O emissions as untreated manure, suggesting that emission differences depend on manure type and its organic nitrogen and carbon content (Vallejo et al., 2006).

Vermicompost also shows a stable C/N ratio and higher NO_3^-/NH_4^+ compared to raw manure, with earthworms enhancing nitrification and shaping microbial community structure (Lazcano et al., 2013). Studies indicate that soil treated with vermicompost produces less N_2O compared to raw manure, though this effect depends on moisture levels (Rodriguez et al., 2011). Manure-derived biochar is another option, known for its stable carbon, nutrient content, and high adsorption capacity, reducing N_2O emissions compared to compost or raw manure (Ribas et al., 2019; Zhu et al., 2014). Biochar can also reduce inorganic nitrogen availability, thus lowering N_2O emissions, although 1–20% of organic nitrogen may mineralize quickly, potentially increasing nitrification (Cayuela et al., 2014).

4. RESULTS AND DISCUSSION

The above studies indicate that organic fertilizers significantly affect the structure and function of microbial communities involved in nitrification and denitrification. Field and incubation studies show that organic fertilization leads to an increase in genes related to nitrification and denitrification, thus increasing N_2O emissions. These changes in soil microorganisms are associated with the availability of nitrogen for nitrification and denitrification, as well as labile carbon that stimulates heterotrophic denitrification, alongside soil conditions such as pH, oxygen availability, texture, and moisture. However, the large variability in the physicochemical properties of organic fertilizers, resulting from different raw materials and processing methods, can have varying effects on soil microorganisms and N_2O emissions.

Climate conditions significantly influence N_2O emissions when organic fertilizers replace synthetic fertilizers, particularly due to the effects of temperature and moisture. Generally, high temperature and moisture levels can increase N_2O emissions by enhancing microbial abundance and nitrogen mineralization rates. However, some studies indicate that increases in average annual temperature and rainfall can inhibit N_2O emissions. This may be because the addition of organic carbon substrates through organic fertilizers leads to complete denitrification, resulting in lower N_2O emissions and increased N_2 production. Thus, the implementation of organic fertilizers instead of synthetic fertilizers in low-rainfall areas may not contribute to N_2O and other greenhouse gas emissions.

Soil texture can also affect N_2O emissions through its impact on soil moisture and aeration. Fine-textured clay soils, with lower aeration and higher moisture retention, increase gas emissions. Sandy soils, which have more air-filled pores, lead to enhanced nitrification and increased N_2O emissions. Compared to plant-derived organic fertilizers, animal-derived organic fertilizers supply more carbon and nitrogen substrates for nitrification and denitrification. Raw manure contains more available carbon and nitrogen than processed manure, such as compost, vermicompost, or digested manure, and requires careful management to prevent gas emissions.

Another approach to enhance the value of manure is pyrolysis for bioenergy production and biochar creation. Manure-derived biochar is a stable carbon source that helps with long-term carbon sequestration and soil amendment due to its nutrient content, large surface area, high porosity, and suitable pH, although some physicochemical properties may change during the production process. Due to its chemical stability, biochar typically produces lower N_2O

emissions than raw or composted manure. Additionally, biochar indirectly affects N_2O emissions by altering soil inorganic nitrogen concentrations; its high adsorption capacity often reduces available inorganic nitrogen and N_2O production. However, between 1% and 20% of organic nitrogen in biochar can rapidly mineralize, increasing nitrification rates. Low-aromatic biochar often contains more labile carbon, potentially enhancing denitrification rates and increasing N_2O emissions. These effects depend on the interaction between biochar and factors such as soil texture, pH, moisture, and nitrogen content. N_2O emissions tend to be higher in acidic soils with coarse texture and high moisture, or in fine-textured soils under low moisture conditions. Finally, the increase in soil pH caused by alkaline biochar may change the dominance and diversity of nitrifying and denitrifying microorganisms.

For raw manure, application rates are sometimes calculated based on phosphorus (P) and potassium (K) instead of nitrogen (N) due to the higher concentrations of these nutrients in manure compared to crop requirements. It is essential to match the added nitrogen to the actual needs of the crops, as emissions rise significantly when nitrogen rates exceed crop demand.

To assess the level of N_2O emissions from agricultural soil, studies have provided specific quantitative data that clarify the impact of various environmental and soil management factors. Below are the key factors, with quantitative details, illustrating their effects on actual N_2O emissions.

Fertilizer Type: The type of fertilizer has a significant impact on N_2O emissions. (Akiyama & Tsuruta, 2003) found that poultry manure generated the highest N_2O emissions, with a total of 184 mg N_2O-N m^2, compared to pig manure (61.3 mg N m^2) and urea (44.8 mg N m^2). Similarly, (Cameron, Di, & Moir, 2013) observed that N_2O emissions from urea can vary from 0% to 65% of the applied N, depending on soil and climatic conditions. (Chu et al., 2007) indicated that synthetic NPK fertilizer also increases nitrification rates and N_2O emissions more than organic fertilizers. Thus, synthetic and high-nitrate fertilizers tend to produce higher N_2O emissions.

Soil pH: Soil pH influences N_2O emissions by regulating denitrifying bacterial activity. (Clough et al., 2003) found that soil at a pH of 6.1 exhibited the highest N_2O emissions at 0.82% of the applied nitrogen, whereas emissions decreased at both higher and lower pH levels. (Davidson et al., 1989) also observed that adjusting soil pH through liming can reduce N_2O emissions. Additionally, (Cole et al., 1997) suggested that pH management could be an effective measure to mitigate greenhouse gas emissions in agriculture.

Soil Temperature: Soil temperature plays a crucial role in determining N_2O emissions. (Davidson et al., 1989) noted that when soil temperature increased up to 35°C, N_2O emissions peaked due to enhanced microbial activity. (Clough et al., 2003) showed that increased temperature in moist soil conditions further promotes N_2O emissions. Therefore, high temperatures stimulate nitrification and denitrification processes in soil, thereby increasing N_2O emissions, especially in moist conditions.

Nitrification Inhibitors: Nitrification inhibitors reduce N_2O emissions by slowing the conversion of ammonium to nitrate. (Akiyama et al., 2000) demonstrated that adding an inhibitor to ammonium sulfate reduced N_2O emissions from 16.4 mg N m^{-2} to 12.7 mg N m^{-2}. Similarly, (Chu et al., 2007) found that adding an inhibitor to synthetic NPK fertilizer significantly lowered N_2O emissions. This indicates that nitrification inhibitors are an effective method for reducing greenhouse gas emissions from agricultural soils when using synthetic fertilizers.

To understand the impact of organic fertilizers on N_2O emissions, it is essential to compare findings from various studies, as the effects can vary based on fertilizer composition and soil management practices. Organic fertilizers generally have a mixed impact on N_2O emissions; some types can significantly increase emissions due to high nitrogen content, while others may help reduce them by enhancing soil structure and microbial balance. The following comparison highlights the different outcomes observed across studies, providing a clearer view of how organic fertilizers can influence N_2O emissions under varying conditions.

The effects of organic fertilizer on N_2O emissions have been extensively studied, with results varying based on fertilizer type, application rate, and soil conditions. For instance, (Akiyama & Tsuruta, 2003) found that poultry manure, a commonly used organic fertilizer, resulted in significantly higher N_2O emissions, reaching 184 mg N_2O-N m^2, compared to pig manure at 61.3 mg N m^2. This contrasts with findings from (Cameron, Di, & Moir, 2013), who noted that the emissions from urea, a synthetic fertilizer, varied more widely from 0% to 65% of applied nitrogen based on soil and environmental factors. Such differences emphasize that organic fertilizers, especially those with high nitrate levels, can contribute to elevated N_2O emissions, comparable to or exceeding those from synthetic fertilizers under certain conditions.

In contrast, organic fertilizers with balanced C/N ratios or composted materials often produce lower emissions. (Chu et al., 2007) observed that synthetic NPK fertilizers increased nitrification rates more than organic manure. They suggested that the gradual nitrogen release from organic manure could mitigate the sharp spikes in N_2O emissions typically associated with synthetic fertilizers. Moreover, (Cole et al., 1997) proposed that organic fertilizers, when used with appropriate soil pH and management practices, could potentially reduce N_2O emissions compared to high-nitrate synthetic fertilizers.

These studies collectively suggest that while certain types of organic fertilizers, such as poultry manure, may increase N_2O emissions due to high nitrate levels, other forms, particularly those with higher carbon content or composted, may help in reducing emissions by improving soil structure and microbial dynamics. Thus, a balanced approach, considering both the type and application conditions of organic fertilizers, can be effective for managing N_2O emissions in agricultural practices.

5. CONCLUSIONS AND RECOMMENDATIONS

Organic fertilizers offer a sustainable alternative to synthetic fertilizers, contributing to healthier soils and ecosystems by enhancing microbial activity and improving nutrient availability, which plays a crucial role in sustainable agricultural practices. The synthesis and emission of N_2O from microbial processes result from complex interactions among factors such as soil temperature, texture, structure, pH, nitrogen availability, degradable organic materials, and water content. Practices like crop rotation, soil mobilization, nitrogen source selection, application rate, timing, and depth all interactively influence N_2O emissions from soil. The diverse physicochemical properties of organic fertilizers, stemming from various input materials and processing methods, lead to varied impacts on soil microorganisms and N_2O emissions. While untreated manure with high moisture content often causes short-term increases in N_2O emissions, especially when crop nitrogen demand is low, processed and stabilized organic fertilizers, such as compost and biochar, tend to produce lower N_2O emissions compared to raw manure and inorganic nitrogen fertilizers. Long-term use of organic fertilizers and increased carbon accumulation in soil help retain nitrogen in the form of microbial biomass or stable organic nitrogen and enhance the abundance of denitrifying microorganisms, promoting complete denitrification to N_2 and thereby reducing N_2O production. To maximize these benefits, it is recommended to use organic fertilizers with balanced carbon-to-nitrogen ratios, like composted manure or biochar, and to apply them with attention to timing, depth, and rate to meet crop nitrogen demand. Regular soil pH adjustments, maintaining an optimal range (around pH 6–7), can further encourage effective denitrification, reducing N_2O emissions. However, this review is limited by variability in study methodologies, climate conditions, and soil types. Further research is needed to standardize approaches for assessing the impact of organic fertilizers on N_2O emissions to provide more consistent and applicable guidance for sustainable agricultural practices.

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