CURRENT TRENDS IN AGRICULTURAL NITROUS OXIDE EMISSIONS: DRIVERS, IMPACTS, AND MITIGATION

Abstract

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential 273 times that of carbon dioxide over a 100-year period, making its emissions a critical environmental challenge. Agricultural practices, particularly nitrogen fertilization, are the primary anthropogenic source of rising N_2O emissions, contributing significantly to global warming and ozone depletion. N_2O emissions in agriculture primarily originate from microbe-mediated soil processes, including nitrification and denitrification, influenced by soil physico-chemical properties such as pH, moisture, and oxygen availability. Additionally, fertilizer type and application methods, manure management, crop residue incorporation, and land-use changes significantly affect emission levels. Climate change further exacerbates N_2O fluxes, with rising temperatures and altered precipitation patterns influencing soil microbial activity and nitrogen transformations. Mitigation strategies for reducing N_2O emissions involve optimizing nitrogen use efficiency through the 4R nutrient management approach (right source, rate, time, and placement), integrating nitrification and denitrification inhibitors, adopting controlled-release fertilizers, and enhancing soil carbon sequestration via biochar application. Moreover, climate-smart agricultural practices, including precision irrigation, reduced tillage, and microbial inoculation, have shown promise in reducing emissions while maintaining crop productivity. Addressing this issue requires a holistic approach that integrates scientific advancements, policy frameworks, and farmer participation to achieve sustainable agricultural intensification while minimizing environmental impacts.

Keywords: Climate change; greenhouse gas; nitrogen cycling; soil microbiology; sustainable agriculture

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I. INTRODUCTION

Nitrous oxide (N_2O) is a significant greenhouse gas with a global warming potential (GWP) of 273 times than carbon dioxide over a period of 100 years. It is a long living greenhouse gas (GHG) in the atmosphere, making its emissions a pressing environmental concern. Thus, understanding its dynamics and source of emission can help in the formulation of effective mitigation strategies and contribute to sustainable development goals. Nitrogen fertilization in agriculture integrated with intensive agricultural practices is the primary source of rising levels of N_2O in the atmosphere [1, 2]. It is the third largest contributor to anthropogenic radiative forcing, exacerbating global warming and ozone depletion [3]. Total N_2O emissions due to anthropogenic factors have surged in the country by 40% from 1980 to 2020 with majority accounting to 3.9 Tg N year^{-1} in 2020 from direct agricultural emission [4]. Despite these alarming trends, some regions such as Europe have made success in reducing emissions by 31% since 1980, by adapting effective mitigation strategies [4]. However, the overall increase in global N_2O emissions underscores the urgent need for comprehensive monitoring and reduction efforts.

II. SOURCES AND MECHANISMS OF N_2O EMISSION IN AGRICULTURE

The mechanisms of N_2O production are complex, involving biological processes such as nitrification and denitrification, which are influenced by various environmental factors (Figure 1).

1. **Soil Microbial Processes:** The process of microbe-mediated N_2O emissions from agricultural soils are mainly nitrification and denitrification. Some of the reported key genes which are mainly responsible for N_2O production are *amoA*, *narG*, *nirS*, *nirK*, and *nosZ*, through different pathways such as ammonia oxidation, nitrate reduction, and denitrification [5]. Such processes are influenced by different soil physico-chemical and biological characteristics such as soil pH, EC, moisture, temperature, oxygen availability, nitrogen content and substrate availability for the microbes [6]. In addition to these factors, environmental conditions and agronomic practices could also significantly affect the amount and frequency of N_2O emissions. The increasing atmospheric CO_2 concentration, resulting to global warming, is expected to increase N_2O emissions by 40.6% and 159.7% respectively [5]. Both nitrification and denitrification may involve the bacterial and fungal population available in the soil [7, 8].

2. **Contribution of Fertilizers and Manure:** Agriculture is one of the primary contributors to N_2O emissions, mainly due to the use of fertilizers and manure as well as the higher emission of N_2O from untreated liquid manure as compared to conventional inorganic fertilizers and decomposed slurry [6, 9]. Additionally, Sarkodie-Addo et al.[10] highlighted the integrated use of inorganic fertilizers with green manure residues could aggravate the emission. Nitrogen fertilization increases N_2O emissions by 153.2%, while biochar application reduces these emissions by 15.8% [5]. For example, Zhang et al.[11] reported that urea is the world's most widely used synthetic nitrogen fertilizer and a significant source of N_2O emissions in agriculture.

3. **Role of Crop Residues and Land Use Changes:** The incorporation of crop residues has a substantial impact on N_2O emissions from agricultural soils. The magnitude and duration of N_2O emissions are determined by factors such as residue quality, soil characteristics, and management practices. Residues with low C:N ratio and high soluble fractions generally lead to higher N_2O emissions [12, 13]. Crop rotation along with conventional tillage practices can result in higher emissions when compared to no-till systems [14]. The impact of residue addition on N_2O emissions was comparative or even higher when compared to the emissions due to the use of synthetic fertilizers, whereas the impact on emissions after assimilation of residue in the soil is influenced by soil parameters such as pH, texture, and moisture content [15].

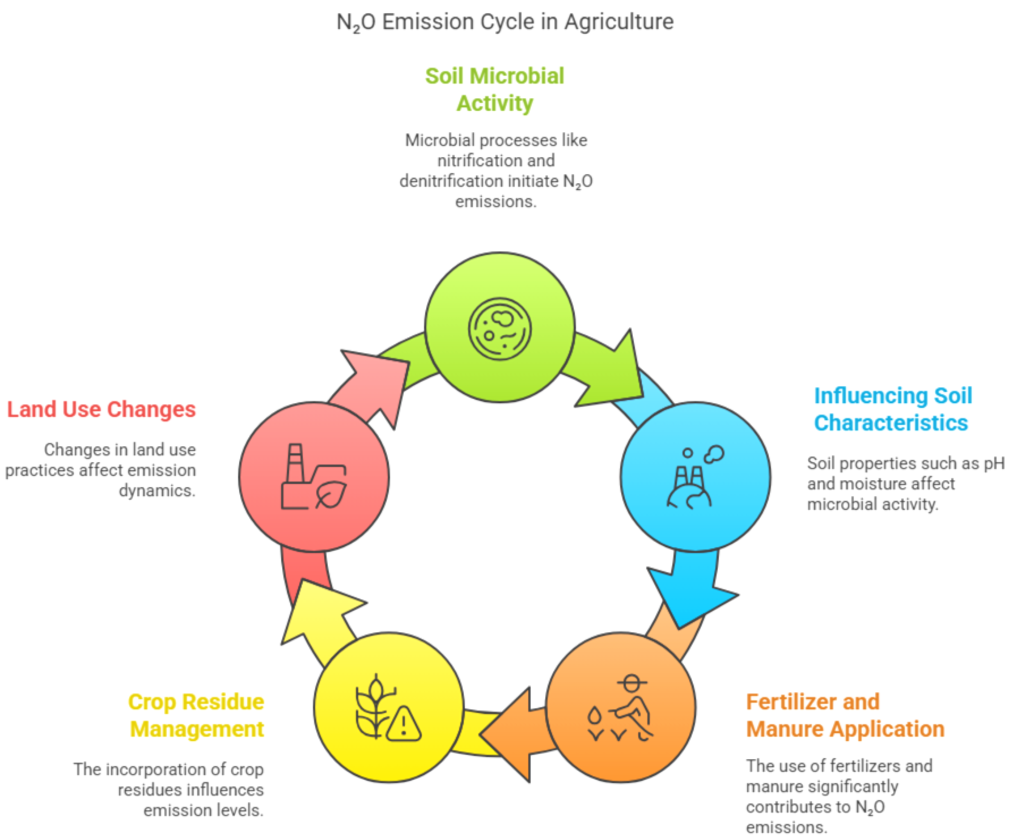

Figure 1: Factors responsible and the underlying mechanisms for N_2O emissions from agricultural land

III. KEY DRIVERS OF RISING AGRICULTURAL N_2O EMISSIONS

The N_2O emissions from agriculture is mainly due to the use of nitrogenous fertilizers and its emission is affected by several interrelated factors such as different agricultural practices, land management, and changing climatic conditions etc. (Figure 2). Hence to effectively mitigate the emissions it is essential to understand the driving mechanism which leads to the emissions.

1. **Intensification of Agricultural Practices:** A major factor in the increase in N_2O emissions has been agricultural intensification, including increased fertilizer application, soil moisture, temperature, and nitrogen content [16, 17]. Seasons and crops have a significant impact on emissions, with grasslands frequently generating more emissions than cereals [16].

2. **Climate Change and Soil Conditions:** Agricultural N_2O emissions are affected by various factors of soil such as moisture conditions playing a crucial role, temperature, and nitrate levels [18]. Both NO and N_2O emissions are significantly increased by nitrogen application rates, with higher emissions occurring in soils with higher levels of organic carbon [19]. Coarse-textured soils with good drainage encourage NO emissions, whereas fine-textured soils with poor drainage and slightly acidic conditions promote N_2O emissions [19]. Iron has been recognized as a frequently overlooked contributor to N_2O production, surpassing other soil properties in explaining emissions under specific conditions [7]. Emission factors range from 0.4% to 6.5% of applied nitrogen, with variations seen among crop varieties, and they change significantly between sites and years [18]. These factors should be considered while developing emission models and inventories.

3. **Land Management and Irrigation Effects:** Research shows that irrigation control has a major effect on N_2O emissions from agriculture. The timing and intensity of irrigation have a significant impact on N_2O fluxes [20] and more water application typically results in greater emissions [20, 21]. However, when compared to traditional ways, deficit irrigation and low-volume techniques such as drip irrigation and zero tillage system can successfully minimize N_2O emissions [22, 23]. Large-scale shifts towards water-efficient irrigation practices can lead to significant reductions in regional N_2O emissions [23].

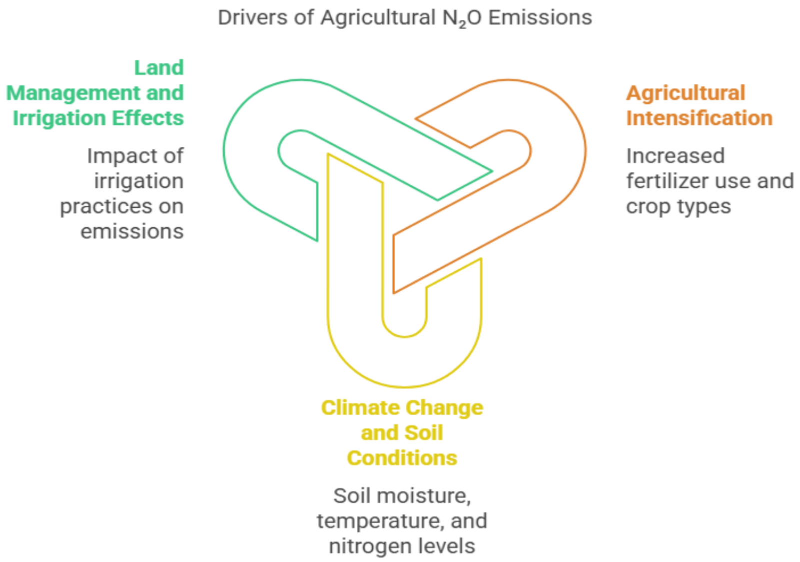

Figure 2: Agricultural practices, land management factors, and changing climatic conditions affecting soil chemistry resulting in elevated N_2O emissions

IV. ENVIRONMENTAL AND CLIMATIC IMPACTS OF N_2O EMISSIONS

1. **Contribution to Global Warming Potential and Ozone Depletion:** N_2O is a powerful greenhouse gas with a global warming potential 273 times greater than CO_2, playing a major role in climate change and ozone layer depletion [24, 25]. As the primary ozone-depleting agent of the 21st century, it has become a serious threat to ozone layer [26]. Stratospheric cooling and changes in air circulation, which reduce NOx output from N_2O, have an impact on how successful N_2O will be in destroying ozone [27]. Furthermore, the quantification of N_2O's effects on ozone is complicated by interacting with other gases, such as CO_2, CH_4, and halo carbons [28]. Both radiative and chemical variables in the higher stratosphere influence how N_2O affects ozone, emphasizing the necessity of complete emission reduction methods [27]. However, efforts to reduce N_2O emissions are severely hampered by climatic criticism. Climate has a significant impact on these emissions, with wet and hotter climates increasing the production of N_2O [25].

2. **Soil Health and Ecosystem Implications:** Air quality, human health, and climate change are all greatly impacted by N_2O emissions from agricultural soils [29]. The nitrogen cycle has been accelerated by anthropogenic activity, which has affected soil health and carbon sequestration and raised N_2O emissions [30]. Soil N_2O emissions are significantly influenced by the diversity and abundance of nosZ genes, which encode N_2O reductase. Soil N_2O emissions are also influenced by non-prokaryotic sources, including chemo-denitrification and fungal denitrification [31].

V. POLICY AND GLOBAL INITIATIVES TO ADDRESS N_2O EMISSIONS

In order to achieve long-term reductions in N_2O emission, an integrated approach of scientific innovation, advanced mitigation technologies, and adaptive policy frameworks with stakeholder engagement needs to be adopted. Global initiatives and policies have been framed in several countries to emphasize sustainable agricultural practices while reducing N_2O emissions from agriculture. For example, the Paris Agreement, signed in 2016, aims to reduce GHG emissions from agriculture through financial and technological support, carbon market mechanisms, and international research collaboration, etc. Additionally, several countries have been advocating certain agricultural practices that enhance nitrogen use efficiencies and incorporating N_2O reduction targets into their Nationally Determined Contributions. The Intergovernmental Panel on Climate Change (IPCC) plays a crucial role in the estimation of GHG emissions and national inventory preparation. It provides standardized methodologies and guidelines to be adopted by countries for emission calculation thus ensuring consistency and accuracy in estimation [32]. It also provides refined and updated methodologies as per scientific advancements hence reducing uncertainty and improving the accuracy of inventories [33]. The Tier I methodology of IPCC is based on empirical methods while the updated Tier II and Tier III methodologies are based on climatic and land use impacts and hence provide more specific emission estimates [34]. The reduction of N_2O emissions is also linked with various SDGs accomplishments. For example, reduction in N_2O emission enhances human health, positively contributes to better ecosystem services, and helps combat climate change. Therefore, this indicates that it is essential to focus on both economic as well as socio-economic balance while achieving N_2O emission reduction. Gu et al.[35] suggested that implementing cost-effective nitrogen control could reduce 72% of the financial burden. Government support mechanisms, incentives, and direct investments further encourage the adoption of sustainable practices, organic farming, etc. [36, 37].

VI. MITIGATION STRATEGIES FOR REDUCING N_2O EMISSIONS

Davidsion and Kanter [38] reported **t**hat agriculture contributes 66% of the total N_2O emission from anthropogenic activities. Keeping in mind the possible negative effects of climate change, mitigation of N_2O emission is crucial. In regard to mitigation strategies, there are several strategies and novel technologies are identified and tested. Some of the climate-smart agricultural practices that can reduce N_2O emissions are discussed below:

1. Integrated use of nitrification and denitrification inhibitors such as 3,4-dimethyl pyrazole phosphate, controlled release fertilizers, and specific microbial consortium [39] with conventional nitrogen fertilizer application are reported to be effective in reducing N_2O emissions. For example**,** Xue et al.[40] reported that nitrification inhibitors can substantially reduce N_2O emissions up to 60% while reducing reactive nitrogen compounds (HONO and NO) by 90%. Similarly, Lam et al.[41] reported 8-57% reduced emissions with such nitrification inhibitors due to improved nitrogen use efficiency (NUE). However, they noticed that there has been an increased trend of ammonia volatilization (3-65%), thus raising doubt on the benefits of increased NUE. Effectiveness of such inhibitors depends upon various factors such as application techniques, climate, and land use. Therefore, to ensure the economic and ecological benefits of such strategies, a careful analysis must be performed before advocating to general masses [42].

2. Optimum application of fertilizer by following 4R approach which is right source, rate, time, and placement which reduces N_2O emissions by optimizing NUE [43]. Since,the key source of N_2O emissions are urea based fertilizers in agriculture [11], Hassan et al.[44] suggested that by application of amendments such as biochar and slow-release fertilizer with nitrification inhibitors can reduce N_2O emissions up to 80% and 50% respectively The application of such amendments does not compromise with the crop yield simultaneously the use of biochar can also aid in carbon sequestration. The carbon loss of biochar over 60 days range between 0.8 to 9.4%, its stability is found to be higher than feedstock materials [45]. Its effectiveness depends on factors such as feedstock properties, soil, climatic conditions, and application rates [46, 47].

3. Adoption of Climate-Smart Agricultural Practices like implementing Climate-Smart Agricultural Practices such as using organic fertilizer and reducing tillage may have different impacts on N_2O emissions [48]. Future mitigation measures could benefit from biological approaches such microbial inoculation with arbuscular mycorrhizal fungus [11].

V. CONCLUSION

Agriculture is a significant contributor of nitrous oxide (N_2O) emissions thus influences climate change, soil health, and sustainable food production to a certain extent. Due to increasing temperature, intensive cultivation, and rigorous use of nitrogenous fertilizers the problem of N_2O emissions have aggravated leading to depletion of the ozone layer and global warming. To address this challenge, an integrated approach of scientific innovation, policy frameworks, and sustainable agricultural practices needs to be incorporated.

Several mitigation strategies for reducing N_2O emissions such as the use of nitrification and denitrification inhibitors, biochar amendments, precision fertilization (4R approach), and climate-smart agricultural techniques were found excellent. These strategies are competent in reducing emissions without compromising with crop productivity. Furthermore, agreements and global initiatives such as the Paris Agreement and IPCC guidelines, are crucial to keep a check on emissions, policy formulations, and plan and promote emission reduction strategies at the national and international levels. In this context, research must continue to refine emission models, develop cost-effective mitigation technologies, and enhance NUE in agricultural systems. By integrating scientific advancements with policy and stakeholder engagement, the agricultural sector can significantly contribute to global efforts in mitigating N_2O emissions, ensuring both environmental sustainability and food security. While the focus on N_2O emissions is critical for climate mitigation, it is also essential to consider the broader context of greenhouse gas emissions and their interrelated effects on global warming and environmental health.

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