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Article

Synthetic fertilizer application strategies for environmentally responsible food production

Violeta Romero-Carrión[1,§]
Julián Ccasani-Allende[1]
César Rivadeneyra-Rivas[1]
Edelina Coayla-Coayla[1]

1 Grupo de Investigación EcoDes-Universidad Nacional Federico Villarreal. Prolongación Camaná Núm. 1 014, Lima, Perú. (jccasani@unfv.edu.pe; crivadeneyra@unfv.edu.pe; acoayla@unfv.edu.pe).

Autor para correspondencia: vromero@unfv.edu.pe.

Abstract

Guaranteeing global food security and mitigating global warming requires optimizing agrifood productivity and reducing emissions of greenhouse gases, such as nitrous oxide (N_2O), which has a global warming potential 300 times greater than that of carbon dioxide (CO_2). In this context, it was proposed to demonstrate that the appropriate application of synthetic fertilizers enables environmentally responsible food production and to identify the impact of reducing nitrous oxide through strategies for the efficient use of synthetic fertilizers. The *ex post facto* design was applied along with a review of the literature in journals indexed in Scopus in 2023 and 2024; various strategies for applying synthetic fertilizers were identified, and the results show that it is necessary to reduce synthetic fertilizers and add biochar or other minerals that maximize the use of nitrogen by plants and minimize environmental emissions; the application of Student's t for 15 studies on wheat, rice, and maize crops revealed with a significance of 1% (p = 0) that the strategies shown on the use of nitrogen fertilizers in crops reduce N_2O emissions. It is concluded that the appropriate application of synthetic fertilizers significantly enables environmentally responsible food production.

Keywords:

climate change, fertilizers, nitrous oxide.

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Introduction

One of the most important challenges for human beings is food production for a growing world population, which entails the need to preserve soil, a non-renewable resource, through sustainable management of carbon storage or sequestration, thereby minimizing environmental impacts (FAO, 2017). The food system is a significant source of greenhouse gas (GHG) emissions from agricultural production, accounting for approximately one-third of global emissions (Crippa *et al*., 2021).

Nitrogen is abundant on our planet; however, the amounts required in soils for food crops are insufficient, so nitrogen fertilizers such as urea (CH_4N_2O) must be applied. Nevertheless, it is necessary to adopt sustainable agricultural practices that positively impact nature and the climate (Hu *et al*., 2023). Nitrogen is crucial for plant nutrition, but its overuse pollutes the atmosphere and accelerates climate change, mainly through emissions of nitrous oxide (N_2O), a potent greenhouse gas (GHG) emitted from farmland and fertilizer application.

The nitrogen cycle involves its natural circulation between the atmosphere, plants, animals, and microorganisms that live on land and in water; natural emissions of N_2O primarily come from bacteria that break down nitrogen on land and in the oceans (EPA, 2025). The economies of China and India show high trends of increase in N_2O from the end of the last century to the present, due to the growing food demand from their populations. On the other hand, in the United States of America, agricultural land is the largest source of N_2O emissions and accounted for approximately 73.9% of total N_2O emissions in 2017 (EPA, 2025).

Likewise, the intensive contribution of synthetic nitrogen (N) in agricultural systems in developing countries is concerning, due to its unfavorable impacts on production and the environment (Yang *et al*., 2024). The above reflects the increase in nitrous oxide today and is illustrated by Figure 1.

Figure 1. Urea is essential for plant metabolism, but it emits N_2O, thereby increasing GHGs. Made with ChatGPT-2025.

The National Oceanic and Atmospheric Administration (NOAA Research, 2025) mentions in its report the acceleration of the growth of atmospheric nitrous oxide, as shown in Figure 2; consequently, rapid action must be taken to reduce GHG emissions and avoid the consequences of global warming, considering that the warming potential of nitrous oxide (N_2O) is significantly

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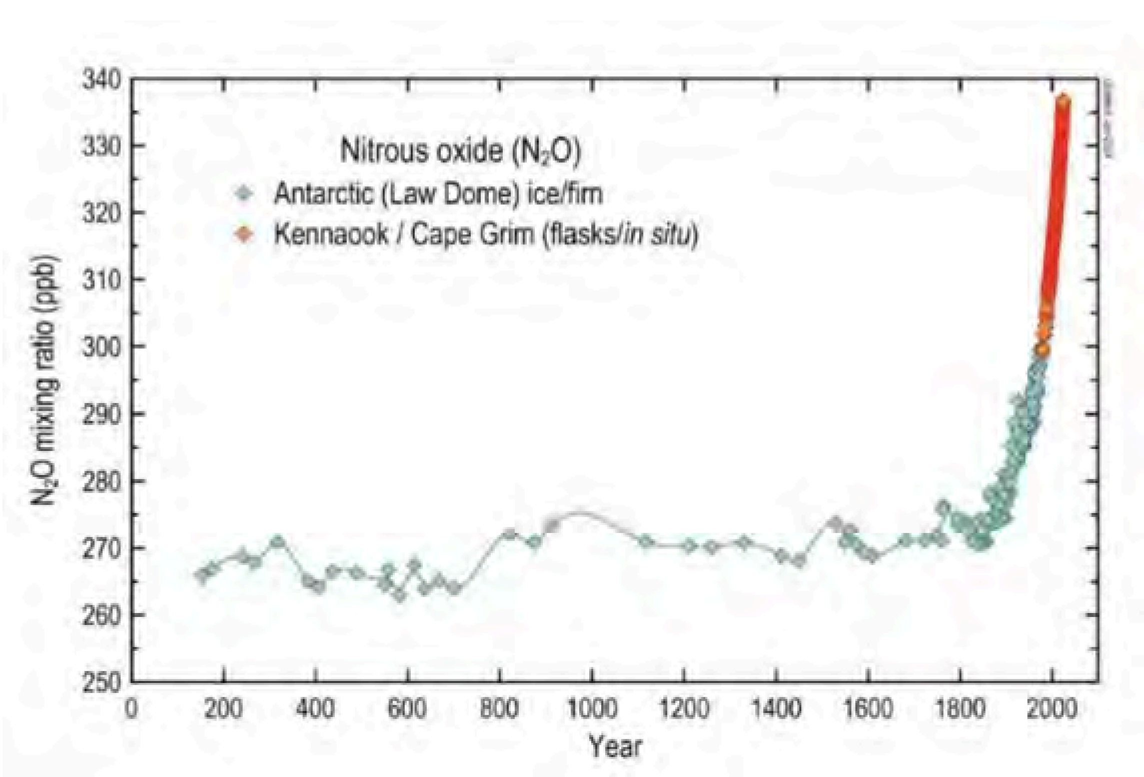
higher than that of carbon dioxide (CO_2) (Griffis *et al*., 2017). The main challenge to reducing N_2O emissions comes from fertilizers applied to crops.

Figure 2. Annual global emissions of nitrous oxide (N_2O) in PPB (NOAA Research, 2025).



Among the negative environmental impacts generated by the agrifood system are the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are largely responsible for current global warming and the deterioration of the ozone layer (Aguilera *et al*., 2020). Within the framework of the food system, the largest contribution to GHGs comes from agriculture and land-use change activities (71%); the rest corresponds to supply chain activities: sales, transport, consumption, waste management, processes, and packaging, among others (Crippa *et al*., 2021).

This finding, identified by Yang *et al*. (2024), considers that global food production faces challenges in balancing the requirement for higher yields with environmental sustainability. Diversified crop rotations increase yields by up to 38%, reduce N_2O emissions by 39%, and improve GHG balance.

Fertilizers

Zabaloy (2021) argues that soils provide humans with food and habitat and influence climate regulation and water retention, among others. However, there are very few soils with sufficient nutrients, making it necessary to enrich them with fertilizers of some kind. Natural fertilizers are formed by natural processes and have not undergone any transformation; these include manure, foliage, mud and ash, among others. In addition, there are synthetic or chemical fertilizers, created by man to provide nutrients to plants, based on phosphorus, potassium and nitrogen.

Sustainable food production

By 2050, food will have to be produced for 10 billion people worldwide, which implies increasing agricultural production by approximately 50%. This must be achieved without expanding the current cultivated area, without resorting to deforestation, or changes in land use, to avoid GHG emissions, which requires optimizing crop yields through the appropriate selection and dosage of fertilizers (IFA, 2024).

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Within the framework of the sustainable development goals (SDGs), Goal 2 on ending hunger and Goal 13 on climate action are interrelated in the continuous systemic interaction of their nature, population, and economy components (Castro-Arce and Vanclay, 2020); in this sense, it is necessary to apply alternatives for better agricultural land management practices. In this context, through a review and analysis of the literature, it was found that the appropriate application of synthetic fertilizers enables environmentally responsible food production and it was possible to identify the impact of nitrous oxide reduction through strategies for the efficient use of synthetic fertilizers.

Materials and methods

The research follows a quantitative, explanatory approach; it uses the independent variable ‘adequate application of synthetic fertilizers’ and the dependent variable ‘environmentally responsible food production’. The design is *ex post facto*, based on data published in journals indexed in Scopus.

Universe

Crops in which nitrogen fertilizers were applied and N_2O emissions were measured. Sample: intentional; 15 cases in which nitrogen fertilizers were applied, and emissions were measured for rice, wheat, and corn crops.

Procedure

A format was developed for data collection, with inclusion criteria such as publications in Scopus in 2023 or 2024 that include applications of nitrogen fertilizers combined with others and measure N_2O emissions. The Shapiro-Wilk test was applied to assess the normality of the data, and, consequently, Student’s t was chosen for the sample.

Results and discussion

Strategies for efficient use of fertilizers to improve global food productivity responsibly

The application of organic and inorganic nitrogen fertilizers is crucial to improving food productivity, but their effectiveness depends on applying strategies that maximize nitrogen utilization by plants and minimize emissions to the environment. Below are some key strategies for nitrogen fertilizer application.

Crop rotations with nitrogen-fixing plants

It is essential to know the region’s soil and climate characteristics to carry out an effective crop rotation. Legumes such as peas, lentils, alfalfa, soybeans, etc., represent a very diverse group of plants that contribute to soil fertility through nitrogen fixation by forming symbiosis with rhizobia (Pérez-Peralta *et al*., 2019). Nitrogen-fixing plants have bacteria in their roots capable of extracting dinitrogen (N_2) from the atmosphere and converting it into ammonia (NH_3), which is part of the plant’s process to have fertile soil and enhance crop productivity.

Optimizing fertilizer application

Choosing the type and dosage of fertilizer, as well as its time of application, can reduce N_2O emissions. More frequent and smaller applications are usually more efficient than large, spaced

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applications (Lu and Tian, 2017). In addition, the amount of water in irrigation, temperature and soil type are variables to consider for dosing fertilizers; among them, one of the most used is urea (CH_4N_2O), due to its water solubility, chemical stability, and low cost compared to other fertilizers.

Nitrification inhibitor technology

This technology comprises two phases: the best-known, for its easy absorption, is the nitrate phase and the most delicate phase is the ammoniacal phase (from urea), but both are required for plant nutrition. Nitrification inhibitors are compounds added to nitrogen fertilizers to reduce nitrogen losses from leaching or volatilization, when the crop adjusts to environmental conditions such as temperature and humidity, which allows greater crop productivity and reduces the emission of N_2O into the environment (Lam *et al*., 2017).

Soil type and cover modification

Modifying soil structure, using techniques such as the addition of organic matter, can increase soil porosity and reduce the accumulation of greenhouse gases. The combination of inorganic nitrogen fertilizers and organic matter can offer significant synergies. Studies have shown that integrating these two practices can improve nitrogen use efficiency, reduce nutrient losses through leaching or volatilization, and improve quality (Ishfaq *et al*., 2023).

Precision agriculture: data-driven soil and fertilization analysis

Precision agriculture (PA), also known as satellite agriculture, consists of conducting soil analysis to determine the needs of fertilizers, such as nitrogen, which allows a more precise and efficient application of fertilizers, avoiding excessive applications and improving nitrogen utilization efficiency (Heffer and Prud'homme, 2017). In the same vein, Coello *et al*. (2025) consider it essential to have accurate datasets to carry out comprehensive analyses that support informed decision-making and policymaking in critical areas, such as food security or climate change, through the use of machine learning models, such as the eXtreme Gradient Boosting and Hist Gradient Boosting algorithms, for predicting the application rates of nitrogen (N), among other fertilizers and serve as an input for various applications, including environmental modeling, causal analysis, fertilizer price predictions and forecasting.

Reduction of N_2O from the agricultural sector in GHG mitigation

Global warming potential (GWP) is defined as a measure that allows the impact of various gases on global warming to be compared, indicating how much energy will be absorbed by the emissions of a tonne of a gas during a specific period, relative to a tonne of CO_2. A higher GWP means that a gas contributes more to global warming than CO_2 over that period, which is typically 100 years (Wypych, 2023).

The main GHGs that contribute to climate change, from highest to lowest proportion in emissions, expressed in (Kiloton CO_2 eq.), are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), among others. Nonetheless, in the opposite direction, we have the global warming potential (GWP), as shown in Figure 3; specifically, the emission of nitrous oxide (N_2O) is lower compared to carbon dioxide (CO_2); nevertheless, its global warming potential is approximately 300 times greater than that of CO_2 over a 100-year period, as mentioned by Griffis *et al*. (2017); Lagos (2025).

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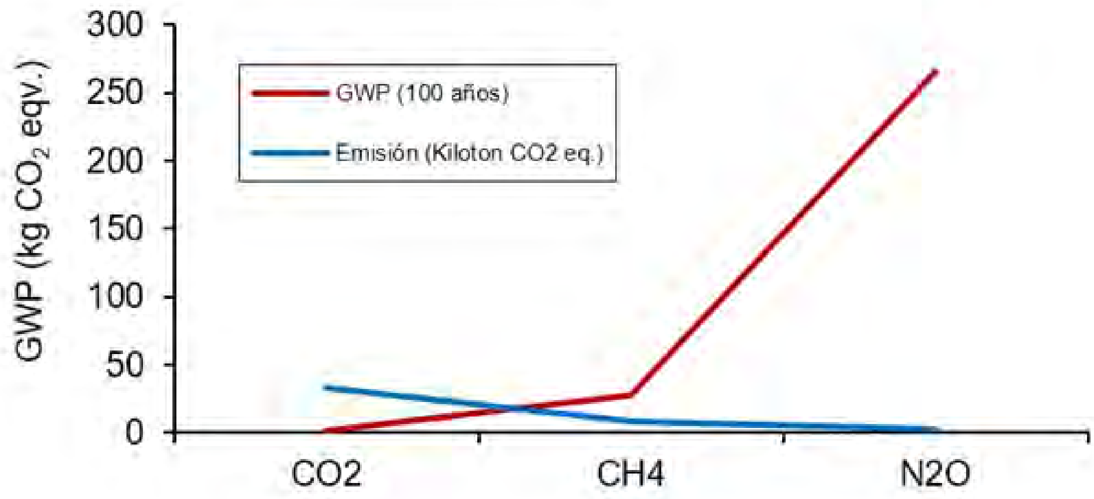
Figure 3. GHG emission and global warming potential (GWP). Prepared using secondary data.



Food systems are responsible for one-third of global anthropogenic GHG emissions, including various economic sectors, as food is grown, harvested, transported, processed, packaged, distributed, and cooked, all of which require energy consumption (Crippa *et al*., 2021). The Colombo declaration calls on the world to cut nitrogen waste in half by 2030 to save 100 billion dollars annually globally, considering this estimate to be half the value of synthetic fertilizer sales. Wu *et al*. (2023) point out that the dosage of mineral and organic fertilizers, irrigation modality, portion of straw returned, no-till, and tillage depth were determining factors in regulating GHG emissions.

Table 1 presents 15 studies published in Scopus-indexed journals that show the effects of percentage reductions in nitrous oxide (N_2O) emissions through efficient strategies applied to rice, wheat, and corn crops. Synthetic nitrogen fertilizers were used, along with the addition of biochar, minerals such as wollastonite or iron slag, straws, or organic fertilizers, among others.

Table 1. Food crop strategies and reduction of N_2O emissions reported in 2023 and 2024.

Author	Strategy synthetic fertilizer +	N_2O reduction (%)
Sun *et al*. (2024)	R straw biochar	25
Lu *et al*. (2024)	W straw biochar	17.5
Zhou *et al*. (2023)	Corn stalk biochar	25.6
Valkama *et al*. (2024)	Biochar/cereals	25
Li *et al*. (2024)	Biochar/vegetables	18.7
Zhang *et al*. (2024)	Biochar and rice-wheat rotation	13.05
Shrestha *et al*. (2023)	Biochar	18
Chen *et al*. (2024)	Wollastonite (mineral) + heat	47.76
Galgo *et al*. (2024)	Iron slag	40
Wang *et al*. (2024)	Rotation of rice and rapeseed crops.	17.9
Dos Reis *et al*. (2024)	Grasslands (-N) F2F farm to fork	15
Zhu *et al*. (2024)	Rhizobionts in corn roots	36
Liu *et al*. (2023)	Garlic-corn crops	40.1
Chiaravalloti *et al*. (2023)	Soil with grain basalt	30.5
Bi *et al*. (2023)	50% organic fertilizer	30.8

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To apply Student's t for a sample, as a hypothesis test, 10% was considered as an expected comparison, based on the fact that organic material inputs in general (crop residues, manure, digestate, compost, and biochar) tend to reduce N_2O emissions by 10% (n= 53) (Valkama *et al*., 2024). The application of the t-statistic with respect to the percentage reduction of N_2O emissions for the 15 experimental cases of wheat, rice, and corn crops is shown in Table 2 with a significance of 1% (p = 0), which allowed us to reject the null hypothesis; consequently, it can be stated that the strategies shown on the use of nitrogen fertilizers in crops reduce the emission of nitrous oxide, mitigating this greenhouse gas and enabling environmentally responsible food production.

Table 2. Application of Student's t for a sample of N_2O reductions, with test value= 10.

	t	df	Sig. (bilateral)	Difference of means	99% confidence interval of the difference	
					Lower	Upper
N_2O reduction (%)	6.158	14	0	16.72733	8.6407	24.8139

In large-scale agriculture, inorganic nitrogen fertilizers, such as urea (with N= 46%), are essential for soil improvement, but they also generate nitrous oxide. Their emissions are indeed lower than those of carbon dioxide, but their global warming potential is almost 300 times greater than that of CO_2. In this sense, we agree with Wang *et al*. (2024), who argue for the need for tillage practices that harmonize productivity with respect for the environment.

The efficient use of inorganic and organic nitrogen fertilizers, the implementation of crops in a sustainable way, such as rotation in planting, nitrification inhibitors, and soil and water management minimize the impact of nitrous oxide on the environment, as shown by Lu and Tian (2017); Lam *et al*. (2017); Ishfaq *et al*. (2023), which is evidenced in this study. Satellite agriculture is a trend; it uses geographic information systems, such as GPS and satellite imagery, that monitor crops for informed decision-making on the application of fertilizers at the correct dose and time, thus optimizing crops, reducing costs, and mitigating emissions, making it possible to meet Sustainable Development Goals two and thirteen. It is possible to mitigate N_2O by using biochar (thermal decomposition of agricultural waste), rotating crops, incorporating minerals such as Wollastonite, using rhizobionts in the roots, and incorporating organic fertilizers.

Conclusions

Strategies for the efficient use of synthetic fertilizers (specifically urea) were identified, such as rotation in planting, nitrification inhibitors, soil management with biochar and minerals, water quantity management and precision agriculture. A significant impact was achieved, with an average reduction of 26.7% in nitrous oxide, resulting from the strategies applied, mainly in wheat, rice and corn crops.

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