

Article

AR6-Harmonized Estimation and Crop-Specific Distribution of Nitrous Oxide Emissions from Agricultural Soils in Pakistan

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Abstract

Accurate assessment of nitrous oxide (N₂O) emissions from agricultural soils is essential for developing effective mitigation strategies. However, Pakistan's current baseline estimates show inconsistencies. The updated Nationally Determined Contributions for 2018 report total greenhouse gas emissions from managed soils at 74.98 Mt CO₂e, while the first Biennial Update Report (BUR 1) estimates N₂O-specific emissions at 70.7 Mt CO₂e, rising under a business-as-usual scenario to 282.8 Mt CO₂e by 2030, an increase of nearly 300%. This study revisits these baselines using verified national datasets from Pakistan's BUR 1 and the National Inventory Report 2021. The 2018 baseline was recalculated using the IPCC Tier 1 methodology, with fertilizer offtake and cropped-area data from national annual reports. Applying the updated IPCC AR6 global warming potential for N₂O (273) revised the BUR 1 2018 estimate to 62.26 Mt CO₂e, closely aligning with the NIR 2021 estimate of 62.4 Mt CO₂e. The study further disaggregates emissions by crop and source. Synthetic fertilizers were the largest direct source of N₂O emissions (14.72 Mt CO₂e), with wheat accounting for 50% (7.36 Mt CO₂e), mainly due to its extensive cropped area. Indirect emissions represented 35% of the revised baseline. Supported by uncertainty and sensitivity analyses, this refined baseline and its crop- and source-specific allocation provide a more reliable and transparent foundation for targeted mitigation in Pakistan's most emission-intensive cropping systems. The findings also highlight the need for crop-specific fertilizer-use surveys to strengthen Tier 1 reporting where country-specific Tier 2 emission factors are unavailable.

Keywords: nitrous oxide; baseline emissions; IPCC Tier 1; global warming potential; synthetic fertilizers; crop-wise apportionment



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1. Introduction

Nitrous oxide (N_2O) is a greenhouse gas (GHG) with a global warming potential 273 times greater than that of carbon dioxide (CO_2) over a 100-year horizon [1]. Since the Industrial Revolution, N_2O has contributed approximately 10% of net global warming [2] and has become the dominant stratospheric ozone-depleting substance emitted in the 21st century [3,4]. Although N_2O emissions are part of the natural nitrogen cycle, anthropogenic sources have driven a 40% increase over the past four decades [4]. Agricultural soils are the primary driver of this increase, with synthetic fertilizers, animal manure, and crop residue additions accounting for the largest share of emissions [5,6]. This trajectory is alarming and diverges from global climate commitments.

Pakistan, unfortunately, lies at the center of this challenge. Its agriculture-based economy employs the majority of the rural workforce and is also the country's leading source of GHG emissions. N_2O emissions from managed soils constitute a significant and growing component of the national GHG inventory [7]. Mitigation strategies—such as optimizing fertilizer use, improving nitrogen use efficiency, and introducing nitrification inhibitors—require a reliable emissions baseline [8].

Pakistan's reporting documents to the United Nations Framework Convention on Climate Change (UNFCCC) reveal inconsistencies in this baseline. The Updated Nationally Determined Contributions [7] report total GHG emissions of 74.98 MtCO_2e from managed soils, whereas the First Biennial Update Report [9] provides a sector-specific figure of 70.7 MtCO_2e for the same year. This discrepancy reflects differences in reporting frameworks, levels of disaggregation, and the use of outdated IPCC AR4 global warming potential (GWP) values. Neither document provides crop-level or source-specific emission breakdowns, nor do they reflect the revised GWP of 273 for N_2O established in the IPCC Sixth Assessment Report (AR6). Correcting this baseline is essential because an overestimated baseline can distort mitigation targets, while the absence of crop- and source-wise disaggregation obscures where interventions can have the greatest impact.

The present study addresses these gaps. We used officially published inventory data and AR6 GWP values to establish a reconciled 2018 baseline for N_2O emissions from Pakistan's agricultural soils and provide the first systematic crop- and source-specific disaggregation of these emissions. Five major crops—wheat, rice, cotton, sugarcane, and maize—which collectively represent more than 80% of the national cropped area and account for the bulk of fertilizer consumption, were analyzed. The study acknowledges limitations in the availability of credible granular data, particularly crop-specific fertilizer-use data, and therefore relies on published region-wise fertilizer offtake and area-weighted crop distribution for analysis and calculations. This highlights the need for a detailed fertilizer-use survey to further refine GHG emissions reporting under the Tier 1 method until Pakistan develops its own crop-specific Tier 2 emission factors. Nonetheless, the current results are intended to strengthen GHG mitigation planning, support Pakistan's NDC commitments, and underpin initiatives such as the USDA-supported Fertilize Right Pakistan project.

2. Materials and Methods

2.1. Data Sources

This study exclusively relies on officially published national reports. This option was deliberate in order to ensure reproducibility and alignment with Pakistan's UNFCCC reporting obligations. The primary sources cover three aspects: national GHG inventory estimates under different reporting frameworks, activity data on fertilizer consumption, and crop area statistics for emission apportionment. Specifically, the following documents were used:

1. Pakistan's Updated NDCs (2021): Provided the total GHG estimate of managed agricultural soil was 74.98 MtCO₂e for 2018 [7].
2. First Biennial Update Report (BUR-1) (GCISC, 2021): Served as the primary source for verified activity data and the adjusted baseline of 70.7 MtCO₂e (GWP-310) [9].
3. Pakistan's Third National Communication on Climate Change (TNC): Used for cross-verification and comparison of emission totals and categorizations [10].
4. National Fertilizer Development Centre (NFDC) Statistics: Supplied data on national nitrogen (N), phosphate (P₂O₅), and potash (K₂O) fertilizer offtake for the fiscal year 2017-18 [11].
5. Pakistan Statistical Yearbook (2018) and Pakistan Economic Survey (2018): Provided data on total cropped area for major crops [12].

Data were organized and analyzed using Microsoft Excel for Office 365 (Version 2606).

2.2. Baseline Recalculation and GWP Adjustment

The N₂O baseline of 70.7 MtCO₂e reported in BUR-1 was originally computed using the IPCC AR4 GWP of 310 for N₂O. In order to align Pakistan's inventory with the most current international standard, this value was recalculated using the AR6 GWP of 273 [13] via a direct proportional adjustment:

$$\text{Adjusted N}_2\text{O Emission (MtCO}_2\text{e)} = 70.7 \text{ MtCO}_2\text{e} \times (273/310) = 62.26 \text{ MtCO}_2\text{e}$$

In order to confirm internal consistency, the resulting value of 62.26 MtCO₂e was then cross-checked against the NIR 2021 reported value of 62.4 MtCO₂e.

2.3. Area-Weighted Crop-Wise Disaggregation of Synthetic Fertilizer Emissions

Crop-wise disaggregation of N₂O emissions is necessary because total national N₂O estimates do not reflect the variations in nitrogen input and emission intensity across different cropping systems. This limits the ability to develop crop-specific and effective mitigation strategies. In this study, five major crops were evaluated: wheat, rice, cotton, sugarcane, and maize. These crops collectively account for over 80% of Pakistan's total cropped area and most of the national fertilizer consumption. Data on crop-specific harvested areas were obtained from the Pakistan Statistical Yearbook (2018) and the Pakistan Economic Survey (2018), while national nitrogen offtake was obtained from the NFDC statistics for 2017–18 [11,12].

Emissions from synthetic fertilizers (16.73 MtCO₂e as per BUR-1 with 310 GWP) were apportioned to major crops using a two-step process:

Step 1: Calculation of National N-use Proportion: The percentage share of nitrogen in the total NPK nutrient offtake for 2017-18 was calculated as:

$$\% \text{ N Share} = (\text{Total N Offtake} / \text{Total NPK Offtake}) \times 100$$

With values from NFDC (N = 3434.82 Gg, NPK = 4763.36 Gg), the % N Share was 72.11%.

Step 2: Apportionment to Crops: The crop-wise N consumption was estimated by applying the national average N application rate (148 kg N/ha, derived from NFDC and cropped area data) to the crop-specific harvested areas for wheat, rice, maize, cotton, and sugarcane:

$$\text{Crop-wise N use} = \text{Crop Area (Mha)} \times 148 \text{ kg N/ha}$$

The share of each crop's N use in the total national N consumption was then used to apportion the total synthetic fertilizer N₂O emissions (14.72 MtCO₂e). The limitation of

this process was the lack of published crop-specific nitrogen rates from official fertilizer-use surveys and farm surveys.

2.4. Correlation Analysis for Arithmetic Consistency

For a consistency check of the disaggregation methodology, a simple linear regression was performed between estimated crop-wise nitrogen consumption and the corresponding apportioned N₂O emissions. Given that the IPCC Tier-1 approach applies a uniform emission factor to nitrogen inputs, a linear relationship provides assurance that no computational errors were introduced in the apportionment.

2.5. Quantitative Uncertainty and Sensitivity Analysis

The uncertainty associated with the recalibrated 2018 N₂O baseline was quantified following the error propagation approach recommended in the IPCC (2006) Guidelines (Vol. 1, Ch. 3) [14].

$$U_{total} = \sqrt{(U_{Fert. \text{ offtake}}^2 + U_{EF}^2 + U_{GWP}^2)} \quad (1)$$

A sensitivity analysis was conducted by varying the N application rate by $\pm 20\%$ and $\pm 40\%$ for each crop group to assess the robustness of the apportionment results, i.e., redistributing total N offtake proportionally to reflect realistic cropping patterns.

3. Results

3.1. Re-Estimated National N₂O Baseline

The NDC (2021) provides only total GHG emissions of 74.98 MtCO₂e from managed soil, while the BUR-1 report provides N₂O emissions of 70.7 MtCO₂e (GWP 310), which was derived from verified activity data and IPCC Tier 1 methodology. After adjusting this value with the AR6 GWP, the reconciled 2018 baseline for N₂O emissions from agricultural soils is 62.26 MtCO₂e (Figure 1). This figure shows a strong alignment with the NIR 2021 reported value of 62.4 MtCO₂e, confirming the validity of the adjusted baseline.

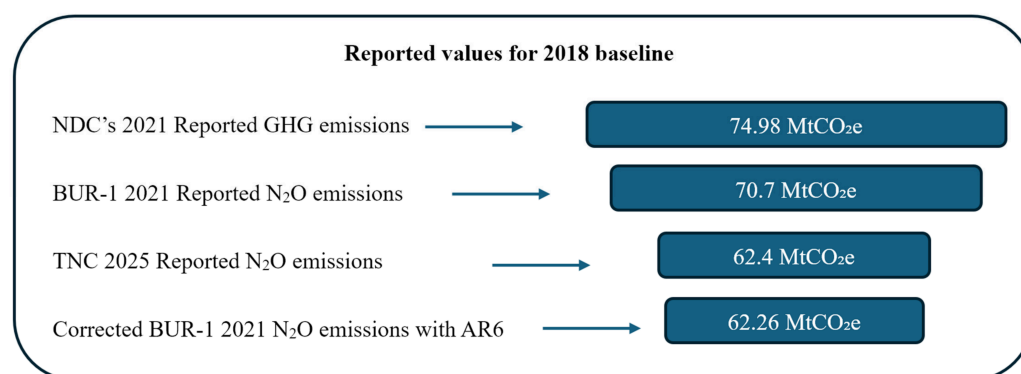


Figure 1. Variations in reported values for 2018 emissions baseline.

3.2. Source-Wise and Crop-Wise Apportionment

The AR6-harmonized baseline of 62.26 MtCO₂e consists of 40.22 MtCO₂e from direct emissions and 22.04 MtCO₂e from indirect emissions. Quantifying indirect nitrogen emissions from agriculture is necessary because a significant fraction of applied nitrogen is lost through volatilization and leaching and subsequently converted into N₂O at locations and times differing from the site and time of fertilizer application, making these emissions distinct from direct soil emissions. The IPCC Guidelines require the separate estimation and reporting of indirect emissions to ensure inventory completeness and to avoid systematic underestimation of the total greenhouse gas impact of agricultural nitrogen

management [15]. This separation also helps in developing effective mitigation strategies by enabling targeted interventions aimed at reducing nitrogen losses along specific pathways [16]. Synthetic fertilizer application was the single largest source of direct emissions, contributing 14.72 MtCO₂e (Figure 2).

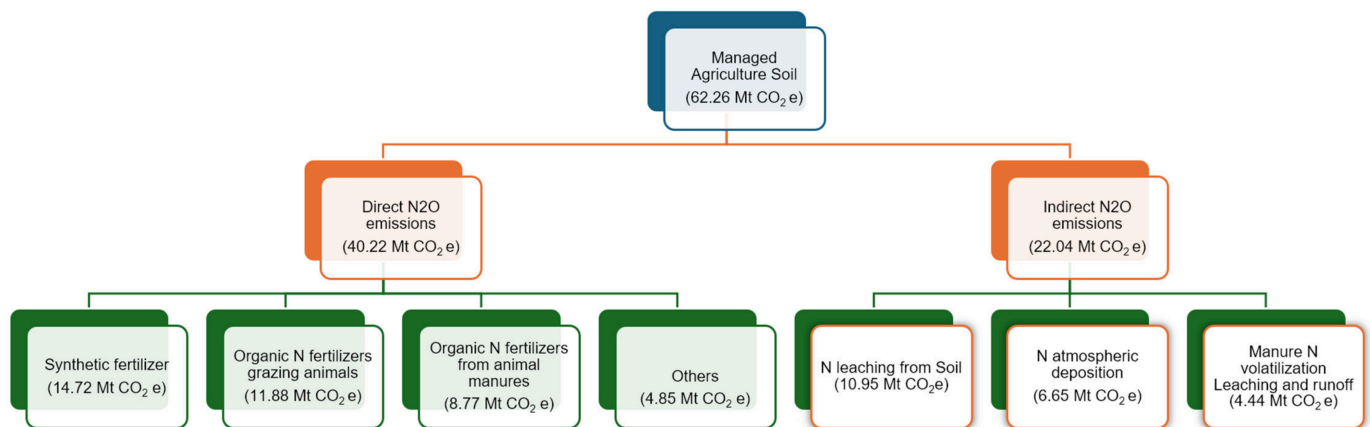


Figure 2. Segregation of gaseous emissions from cultivated agricultural soils.

Among the five crops analyzed, wheat dominated the synthetic fertilizer N₂O footprint, accounting for 50% of apportioned emissions (7.36 MtCO₂e) based on reported cropped area and uniform-rate scenario (Figure 3). This was followed by cotton (25%, 3.68 MtCO₂e), sugarcane (8%, 1.18 MtCO₂e), rice (6%, 0.88 MtCO₂e), and maize (1%, 0.15 MtCO₂e). Confirming the methodological integrity of this apportionment, a near-perfect linear relationship ($R^2 = 0.9999$) was found between crop-wise nitrogen consumption and apportioned N₂O emissions (Figure 4), consistent with the IPCC Tier 1 framework's application of a uniform emission factor to nitrogen inputs. Furthermore, this relationship highlights that reductions in nitrogen fertilizer use would yield proportional reductions in direct N₂O emissions.

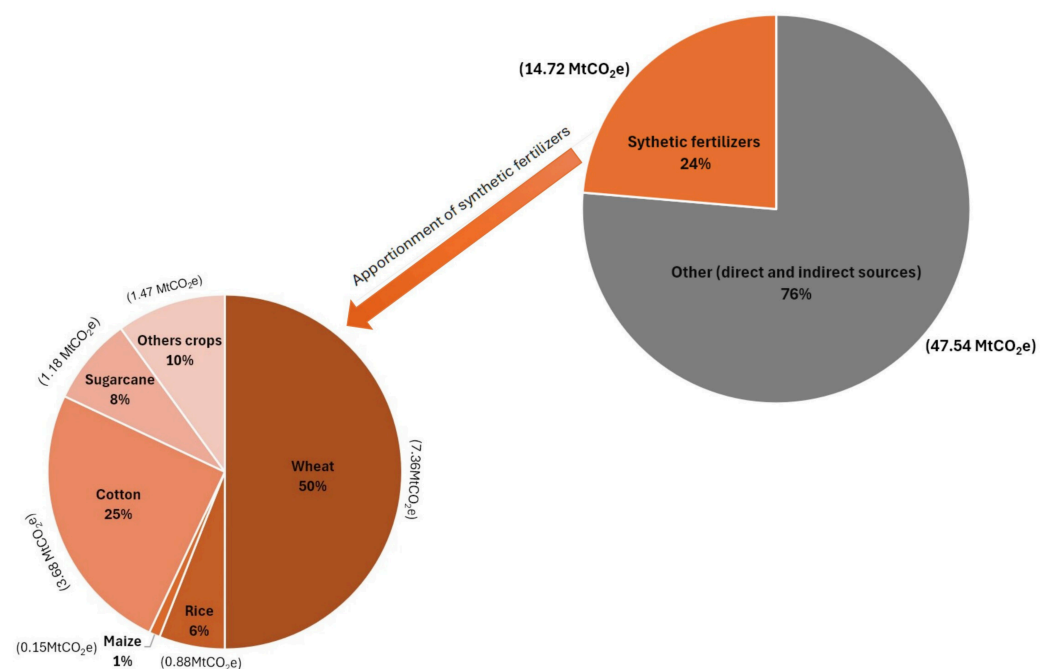


Figure 3. Total N₂O emissions and apportionment from synthetic fertilizers.

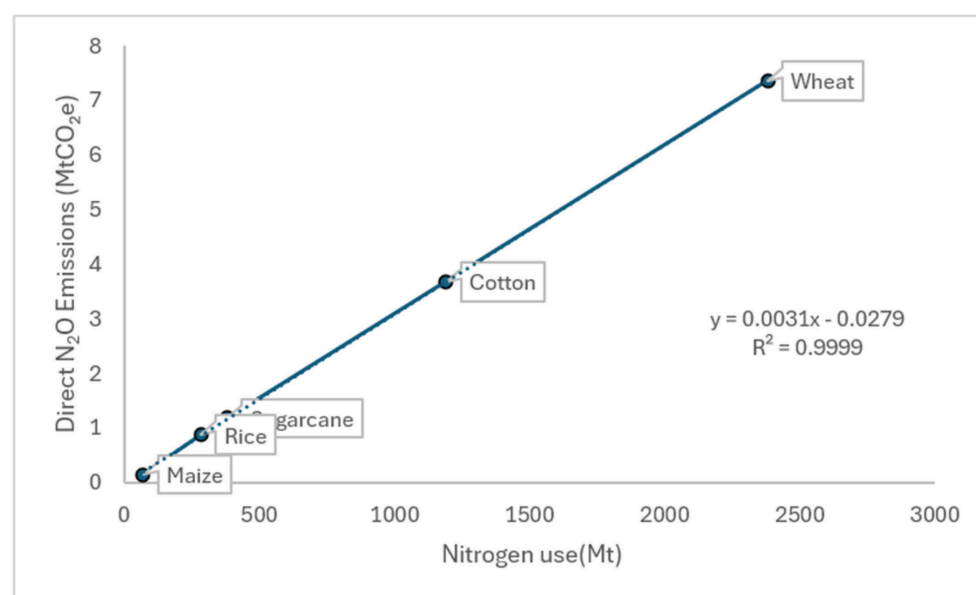


Figure 4. Consistency verification for crop-wise allocation of N-emissions.

3.3. Quantitative Uncertainty and Sensitivity Analysis

For the recalibrated 2018 N₂O baseline, the input uncertainties were assigned based on default IPCC guidance (50% for Tier 1 emission factors, 15% for national fertilizer offtake data, and 2% for the AR6 GWP value) [14]. The combined relative uncertainty for direct N₂O emissions from synthetic fertilizers was calculated as $\pm 52\%$ (root sum square), while the total baseline (including indirect emissions) exhibited a combined uncertainty of $\pm 48\%$ (Table 1).

Table 1. Uncertainty budget for the recalibrated 2018 N₂O baseline (62.26 MtCO₂e).

Parameter	Value	Assigned Uncertainty (%)	Source of Uncertainty
Total N fertilizer consumption (Gg N)	3434.8	$\pm 15\%$	NFDC offtake data, sampling variability
Direct N ₂ O emission factor (EF ₁)	0.01	$\pm 50\%$	IPCC (2006) default for Tier 1
Indirect emission factor (volatilization, EF ₄)	0.01	$\pm 50\%$	IPCC (2006) default
Indirect emission factor (leaching, EF ₅)	0.0075	$\pm 50\%$	IPCC (2006) default
GWP (AR6) for N ₂ O	273	$\pm 2\%$	IPCC (2023)
Combined uncertainty (direct emissions)	—	$\pm 52\%$	Root sum square
Combined uncertainty (total baseline)	—	$\pm 48\%$	Root sum square

A sensitivity analysis was conducted to test the assumption of a uniform nitrogen application rate (148 kg N/ha) across major crops by varying the rate by $\pm 20\%$ and $\pm 40\%$ for each crop while holding total national N offtake constant. The results in Table 2 demonstrate that the ranking of crops by emission magnitude (wheat > cotton > sugarcane > rice > maize) did not change. Wheat was responsible for the highest direct N₂O emissions from synthetic fertilizers, ranging from 4.42 to 10.30 MtCO₂e depending on the rate assumption. This stability indicates that the primary conclusion that wheat cultivation is the dominant emission hotspot is robust to reasonable variations in crop-specific N application rates.

Table 2. Sensitivity of crop-wise direct N₂O emissions (MtCO₂e) to changes in assumed N application rate.

Crop	Baseline (148 kg N ha ^{−1})	−40% Rate	−20% Rate	+20% Rate	+40% Rate	Rank Stability
Wheat	7.36	4.42	5.89	8.83	10.30	1st
Cotton	3.68	2.21	2.94	4.42	5.15	2nd
Sugarcane	1.18	0.71	0.94	1.42	1.65	3rd
Rice	0.88	0.53	0.70	1.06	1.23	4th
Maize	0.15	0.09	0.12	0.18	0.21	5th

4. Discussion

4.1. The Imperative for Baseline Reconciliation

Pakistan's NDC, BUR-1, and NIR 2021 report three different estimates for agricultural soil emissions for the same reference year. This discrepancy is more than an accounting issue; it reflects a structural challenge in national GHG inventories, where successive reporting cycles can introduce methodological differences faster than they are reconciled, particularly when reports use different GWP values, sectoral boundaries, and activity data sources. The NDC estimate of 74.98 MtCO₂e aggregates gases and sectors without N₂O-specific resolution, while the BUR-1 estimate of 70.7 MtCO₂e is more detailed but based on the GWP-310 standard. Neither estimate is incorrect, but neither provides a suitable baseline for future projections or mitigation planning. The difference underscores the need for crop-specific reporting based on bottom-up activity data to support credible and verifiable national inventories in line with IPCC guidance [17].

This analysis reconciles the reported values and updates the agricultural N₂O baseline to 62.26 Mt CO₂e using the IPCC Sixth Assessment Report (AR6) global warming potential (GWP) value of 273. This adjustment corrects the overestimation associated with earlier conversion factors and aligns Pakistan's reporting with current IPCC inventory methodologies [13]. The revised baseline provides a clearer basis for identifying priority mitigation opportunities in managed soils and establishes a robust reference point for tracking the impact of mitigation initiatives, including USDA-funded initiatives such as the Fertilize Right Pakistan project.

4.2. Dominance of Wheat and Synthetic Fertilizers

The disaggregated results show that wheat accounts for approximately 50% of synthetic fertilizer-related N₂O emissions, exceeding the combined contributions of rice, cotton, and sugarcane. This outsized share reflects both the scale of wheat cultivation and the long-standing tendency toward excessive nitrogen application. With around 9 million hectares under wheat and average application rates that often exceed crop nitrogen demand, wheat offers the largest absolute mitigation opportunity of any single crop [18]. Cotton, although cultivated on a smaller area, has a disproportionately high nitrogen footprint because of its fertilizer intensity, and its 25% share of emissions also warrants targeted attention.

Although the relationship is linear and arithmetic, the strong correlation between nitrogen use and N₂O emissions ($R^2 = 0.9999$) has an important practical implication: every kilogram of unnecessary nitrogen application directly increases emissions. Fertilizer management should therefore be a primary mitigation strategy, and the crop-level apportionment clearly shows where this strategy should be applied first.

The 4Rs of Nutrient Stewardship—applying the right fertilizer source, at the right rate, at the right time, and in the right place—provide an established framework for reducing fertilizer-based N₂O emissions across these cropping systems [19]. In Pakistan's wheat–

cotton system, the 4R approach offers a practical and scalable pathway to improve fertilizer use efficiency and reduce N_2O emissions. Applying the right source involves replacing conventional urea with enhanced-efficiency fertilizers, such as nitrification inhibitors or polymer-coated fertilizers, which can reduce direct N_2O emissions by 20–50% in cereal systems [1,20]. The right rate principle addresses blanket fertilizer application that often exceeds crop demand by promoting site- and variety-specific rates based on soil testing and yield targets. Applying fertilizer at the right time means avoiding periods of excessive soil moisture and low crop demand, such as the pre-monsoon period or early sowing stages; these practices can also reduce indirect N_2O emissions through lower leaching losses [21]. Right placement methods, such as subsurface banding, dibbling, or fertigation, can improve nitrogen uptake efficiency and reduce losses. Even a modest 20% improvement in nitrogen use efficiency across wheat-growing districts through the 4Rs could reduce N_2O emissions by approximately 1.1 MtCO_2e annually, supporting Pakistan's NDC commitments and the objectives of the Fertilize Right Pakistan initiative.

4.3. The Significant Role of Indirect Emissions

Indirect N_2O emissions amount to 22.04 MtCO_2e , or 35% of the revised baseline, and are too substantial to ignore. These emissions are mainly driven by nitrogen volatilized as NH_3 and NO_x that is later deposited and nitrified or denitrified elsewhere (6.65 MtCO_2e from atmospheric deposition), and by nitrogen leached as NO_3^- into waterways and groundwater (10.95 MtCO_2e from leaching). Together, these fluxes clearly reflect the inefficiency of Pakistan's agricultural nitrogen management system.

Strategies that improve nitrogen use efficiency (NUE) by reducing application rates and better matching fertilizer supply with crop demand can address both direct and indirect emission pathways. Controlled-release fertilizers, improved timing and placement, and cover crops that capture residual soil nitrogen can reduce leaching and volatilization losses across cropping systems [22]. Pakistan's mitigation strategy should therefore address not only direct emissions but also the larger indirect loss stream identified by the data.

4.4. Implications of Uncertainty and Robustness of Crop-Wise Apportionment

A quantitative uncertainty analysis shows that the AR6-adjusted 2018 N_2O baseline of 62.26 MtCO_2e has an average relative uncertainty of approximately $\pm 48\%$. This level is consistent with other national-scale Tier 1 inventories for agricultural N_2O emissions. For example, [23] reported similar uncertainty ranges (40–60%) for the UK agricultural GHG inventory, with direct emissions contributing most to overall uncertainty. In this analysis, the default IPCC EF_1 value (0.01) for fertilizer-derived N_2O accounts for most of the uncertainty. This high uncertainty reflects the inherent limitation of applying a globally generalized Tier 1 emission factor to locally heterogeneous conditions. It also highlights the need for Pakistan to develop country-specific Tier 2 emission factors through field measurements across its major cropping zones [24]. Studies show that reducing uncertainty in EF_1 by 50% could lower the combined uncertainty of direct emissions from $\pm 52\%$ to approximately $\pm 37\%$, substantially improving the reliability of the national inventory.

The sensitivity analysis shows that these uncertainties do not alter the central finding. Whether crop-specific nitrogen application rates vary by $\pm 20\%$ or $\pm 40\%$ from the national average, wheat remains the largest emission source among the crops analyzed, and the ranking is unchanged. Although data limitations required the use of a uniform nitrogen application rate, this assumption does not bias the identification of wheat as the dominant emission source. This finding is consistent with the fact that wheat covers the largest cropped area in Pakistan, approximately 9 million hectares, and is therefore the largest recipient of nitrogen even when actual application rates vary by region [18]. The sensitivity

analysis further shows that wheat would still rank first even if it received 40% less nitrogen than the national average. Therefore, interventions focused on nitrogen management in wheat systems are likely to deliver the highest mitigation benefits despite residual uncertainty in crop-specific application rates.

One limitation of the uniform application-rate assumption requires attention. Sugarcane generally receives above-average nitrogen fertilizer rates, so its emissions may be underestimated in this apportionment. Conversely, crops in rainfed zones typically receive below-average inputs [25]. These biases affect absolute crop-level estimates but do not change the overall ranking.

4.5. Limitations and Future Inventory Improvements

This analysis relies on the IPCC Tier 1 methodology and national-average data. Although this approach is methodologically sound for national-scale baselines, it lacks spatial and temporal specificity and does not distinguish between irrigated wheat systems in Punjab and rainfed systems in the Pothohar region. The difference between BUR-1 and NIR 2021 estimates reflects ongoing refinements in national inventory methods. Future efforts should focus on developing country-specific Tier 2 emission factors through field measurements, particularly for major cropping systems such as wheat–cotton and wheat–rice rotations [2]. Integrating soil type, climate data, and management practices into the inventory would further improve the accuracy of country-level mitigation policies. Pakistan should also establish a formal GWP-update protocol so that future changes, such as a transition from AR6 to AR7 values, are applied consistently across all climate reporting documents.

5. Conclusions

This study systematically reevaluated and harmonized the 2018 baseline for N₂O emissions from Pakistan's agricultural soils, establishing an updated value of 62.26 MtCO₂e based on verified inventory data and the latest IPCC AR6 GWP. Wheat cultivation accounts for the majority of synthetic fertilizer-related N₂O emissions and should therefore be the primary target for mitigation. The 4Rs of Nutrient Stewardship provide a practical, farmer-led framework for reducing nitrogen losses in agriculture. Indirect emissions, which account for about one-third of the total baseline, also require greater attention in future mitigation strategies.

Disaggregating the national aggregate enables Pakistan's agricultural GHG accounting to move beyond description toward a crop- and source-specific understanding of emissions. This analysis can help stakeholders design targeted strategies to reduce agricultural N₂O emissions, support Pakistan's climate goals, and promote more sustainable agricultural development.

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References

1. Abalos, D.; Jeffery, S.; Sanz-Cobena, A.; Garnier, J.; Aguilera, E.; Castellano, M.J. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. *Agric. Ecosyst. Environ.* **2014**, *189*, 136–148. [CrossRef]
2. Butterbach-Bahl, K.; Baggs, E.M.; Dannenmann, M.; Kiese, R.; Zechmeister-Boltenstern, S. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130122. [CrossRef]
3. Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st century. *Science* **2009**, *326*, 123–125. [CrossRef]
4. Tian, H.; Xu, R.; Canadell, J.G.; Thompson, R.L.; Winiwarter, W.; Suntharalingam, P.; Davidson, E.A.; Ciais, P.; Jackson, R.B.; Janssens-Maenhout, G.; et al. Global nitrous oxide budget (1980–2020). *Earth Syst. Sci. Data* **2024**, *16*, 2543–2604. [CrossRef]
5. Tian, H.; Xu, R.T.; Canadell, J.G.; Thompson, R.L.; Winiwarter, W.; Suntharalingam, P.; Davidson, E.A.; Ciais, P.; Jackson, R.B.; Janssens-Maenhout, G.; et al. A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* **2020**, *586*, 248–256. [CrossRef]
6. Intergovernmental Panel on Climate Change (IPCC). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019. Available online: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/> (accessed on 15 May 2026).
7. Ministry of Climate Change (MoCC). *Pakistan Updated Nationally Determined Contributions (NDCs) 2021*; Government of Pakistan: Islamabad, Pakistan, 2021. Available online: <https://unfccc.int/sites/default/files/NDC/2022-06/Pakistan%20Updated%20NDC%202021.pdf> (accessed on 3 April 2026).
8. Shaaban, M.; Wu, Y.; Wu, L.; Hu, R.; Younas, A.; Nunez-Delgado, A.; Xu, P.; Sun, Z.; Lin, S.; Xu, X.; et al. The effects of pH change through liming on soil N₂O emissions. *Processes* **2020**, *8*, 702. [CrossRef]
9. Global Change Impact Studies Centre (GCISC). *Pakistan's First Biennial Update Report (BUR-1)*; Ministry of Climate Change: Islamabad, Pakistan, 2021. Available online: [https://unfccc.int/sites/default/files/resource/Pakistan%E2%80%99s%20First%20Biennial%20Update%20Report%20\(BUR-1\)%20-%202022.pdf](https://unfccc.int/sites/default/files/resource/Pakistan%E2%80%99s%20First%20Biennial%20Update%20Report%20(BUR-1)%20-%202022.pdf) (accessed on 15 May 2026).
10. Ministry of Climate Change (MoCC). *Pakistan's Third National Communication on Climate Change to the United Nations Framework Convention on Climate Change*; Government of Pakistan: Islamabad, Pakistan, 2025. Available online: <https://unfccc.int/sites/default/files/resource/TNC%20Report%2027-6-25.pdf> (accessed on 23 April 2026).
11. Ministry of National Food Security and Research. *Pakistan Fertilizer Statistics 2012–13 to 2022–23*; National Fertilizer Development Centre: Islamabad, Pakistan, 2023. Available online: <https://nfdc.gov.pk/publications/Pakistan%20Fertilizer%20Statistics.pdf> (accessed on 15 May 2026).
12. Government of Pakistan, Finance Division. *Pakistan Economic Survey 2017–18. Economic Adviser's Wing. 2018*. Available online: https://www.finance.gov.pk/survey/chapters_19/Economic_Survey_2018_19.pdf (accessed on 7 January 2026).
13. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021. [CrossRef]
14. Intergovernmental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Hayama, Japan, 2006. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_0_Cover.pdf (accessed on 27 February 2026).
15. Tian, L.; Cai, Y.; Akiyama, H. A review of indirect N₂O emission factors from agricultural nitrogen leaching and runoff to update the default IPCC values. *Environ. Pollut.* **2019**, *245*, 300–306. [CrossRef]
16. Gnisia, G.; Weik, J.; Ruser, R.; Essich, L.; Lewandowski, I.; Stein, A. Machine learning-based prediction of nitrous oxide emissions from arable farming: Exploring management practices as predictor variables. *Ecol. Indic.* **2025**, *172*, 113233. [CrossRef]
17. Smith, P.; Soussana, J.F.; Angers, D.; Schipper, L.; Chenu, C.; Rasse, D.P.; Batjes, N.H.; van Egmond, F.; McNeill, S.; Kuhnert, M.; et al. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Glob. Change Biol.* **2020**, *26*, 219–241. [CrossRef]
18. Shakoor, A.; Shahzad, S.M.; Chatterjee, N.; Arif, M.S.; Farooq, T.H.; Altaf, M.M.; Tufail, M.A.; Dar, A.A.; Mehmood, T. Nitrous oxide emission from agricultural soils: Application of animal manure or biochar? A global meta-analysis. *J. Environ. Manag.* **2021**, *285*, 112170. [CrossRef]
19. International Fertilizer Industry Association (IFA). *The Global “4R” Nutrient Stewardship Framework for Developing and Delivering Fertilizer Best Management Practices*; IFA: Paris, France, 2009. Available online: https://www.fertilizer.org/wp-content/uploads/2023/01/2009_ifa_agcom_FBMps.pdf (accessed on 4 May 2026).

20. Zaman, M.; Nguyen, M.L.; Saggar, S. N₂O and N₂ emissions from pasture and wetland soils with and without amendments of nitrate, lime, and zeolite under laboratory conditions. *Soil Res.* **2018**, *46*, 526–534. [[CrossRef](#)]
21. Matse, D.T.; Krol, D.J.; Richards, K.G.; Danaher, M.; Cummins, E.; Wang, X.; Forrester, P.J. Fertiliser nitrogen source and the use of nitrification inhibitors are tools to reduce nitrous oxide emissions and improve agronomic performance in temperate grassland. *Environ. Technol. Innov.* **2025**, *39*, 104232. [[CrossRef](#)]
22. Cui, Z.L.; Wu, L.; Ye, Y.L.; Ma, W.Q.; Chen, X.P.; Zhang, F.S. Trade-offs between high yields and greenhouse gas emissions in irrigation wheat cropland in China. *Biogeosciences* **2014**, *11*, 2287–2294. [[CrossRef](#)]
23. Milne, A.E.; Glendining, M.J.; Bellamy, P.; Misselbrook, T.; Gilhespy, S.; Casado, M.R.; Hulin, A.; van Oijen, M.; Whitmore, A.P. Analysis of uncertainties in the estimates of nitrous oxide and methane emissions in the UK's greenhouse gas inventory for agriculture. *Atmos. Environ.* **2014**, *82*, 94–105. [[CrossRef](#)]
24. Hergoualc'h, K.; Akiyama, H.; Bernoux, M.; Chirinda, N.; del Prado, A.; Kasimir, Å.; MacDonald, J.D.; Ogle, S.M.; Regina, K.; van der Weerden, T. N₂O emissions from managed soils, and CO₂ emissions from lime and urea application. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019; pp. 11.1–11.48. Available online: <https://hdl.handle.net/10568/107142> (accessed on 4 May 2026).
25. Baig, M.B.; Shahid, S.A.; Straquadine, G.S. Making rainfed agriculture sustainable through environmental friendly technologies in Pakistan: A review. *Int. Soil Water Conserv. Res.* **2013**, *1*, 36–52. [[CrossRef](#)]

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